THE OCEANOGRAPHY OF
SANTA MONICA BAY, CALIFORNIA

Volume II

by

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and

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A Final Report
submitted to the Hyperion Engineers,
by the Geology Department,
University of Southern California
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For

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and

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of 5^{o} or more were required in the inshore area to retain the desired track, which were followed in a few minutes by similar corrections in the opposite direction. These fluctuations in the water motion were not due to tidal action, for the same corrections were necessary on subsequent traverse lines to remain on course.

WATER SALINITY AND NUTRIENTS

Methods

Salinity determinations were made using the titration methods described by Knudsen (1901). Only one titration was made per sample, except in cases where the results were questionable. At intervals checks were made on randomly chosen samples. The results of some of these are shown in Table V. In addition, a series of repeat analyses were made to determine if variations existed due to the different types of bottles used for collection. These data are shown in Table VI. To minimize the changes due to storage, samples were stored in the same type of bottles aboard ship and analyzed immediately after each cruise. No salinity determinations were made aboard ship.

Subsurface samples were collected from Nansen bottles except for some bacteriological stations where the water sample collected for bacteria determinations was later used for salinity analysis. This, of course, was necessary in order to eliminate the chance of sampling different parts of the variable nearshore diluted water.

Surface samples were collected with a large rubber bucket.

TABLE V

SAMPLE TITRATIONS INDICATING PRECISION OF OPERATOR

Sample Number	Duplicate Titrations	Average Cl^-
1014, 3/28/56	18.61 18.60 18.61	18.61
1104, 3/28/56	18.60 18.60 18.61	18.60
1252, 3/28/56	18.60 18.59 18.60	18.60
1316, 3/28/56	18.62 18.62 18.62	18.62
1342, 3/28/56	18.61 18.61 18.61	18.61

TABLE VI

COMPARISON OF BOTTLES USED FOR WATER SAMPLES

Station Number	Bottle Type	Initial Chlorinity	Final Chlorinity
4217-56	A	17.34	17.49
	B	17.35	17.35
	C	17.36	17.41
4218-56	A	17.93	18.07
	B	17.96	18.00
	C	17.95	17.96
4219-56	A	18.24	18.34
	B	18.24	18.23
	C	18.24	18.23
4220-56	A	17.77	17.89
	B	17.77	17.78
	C	17.76	17.76
4221-56	A	18.48	18.56
	B	18.48	18.48
	C	18.49	18.49
4224-56	A	18.42	18.56
	B	18.43	18.43
	C	18.43	18.42

The initial chlorinity was determined within four days after collection. The final chlorinity was titrated three and one-half months after collection.

Polyethylene bottle A was capped with an ordinary plastic screw cap.

The citrate bottle B was standard with a glass cap and a rubber ring seal.

Polyethylene bottle C was capped with a plastic-cone-seal screw top. This latter type of seal was the standard used on this survey.

Equipment

The Nansen bottles were used, as noted previously, for obtaining subsurface samples. Reversing thermometers were placed on each bottle in order that the temperature and density of the water sampled at particular levels could be determined. The water samples collected during the bacteria studies were obtained with a slightly modified Zobell Bacteria Sampler.

Additional Sources of Salinity Data

Personnel of the Los Angeles City Bureau of Sanitation, directed by C. G. Gunnerson, have collected numerous water samples in Santa Monica Bay during the past two to three years. Chlorinities were determined by silver nitrate titration, but a potentiometric end-point was used. The chlorinities obtained for identical water samples by both Hyperion and Hancock Foundation show that the values differed by about 0.06 o/oo, or about 0.11% in salinity (Table VII). This is a rather large difference, and in any future work the two methods should be more carefully compared and the source of error eliminated.

Some salinity data gathered by the Scripps Institution of Oceanography were examined, but their stations lay beyond the area of investigation in almost all cases.

Salinity Data for Shelf Water

Vertical Variation

The vertical chlorinity variation in the bay as a whole is shown in Figure 72, in which the chlorinity is plotted against depth for the shelf water down to 300 feet.

TABLE VII

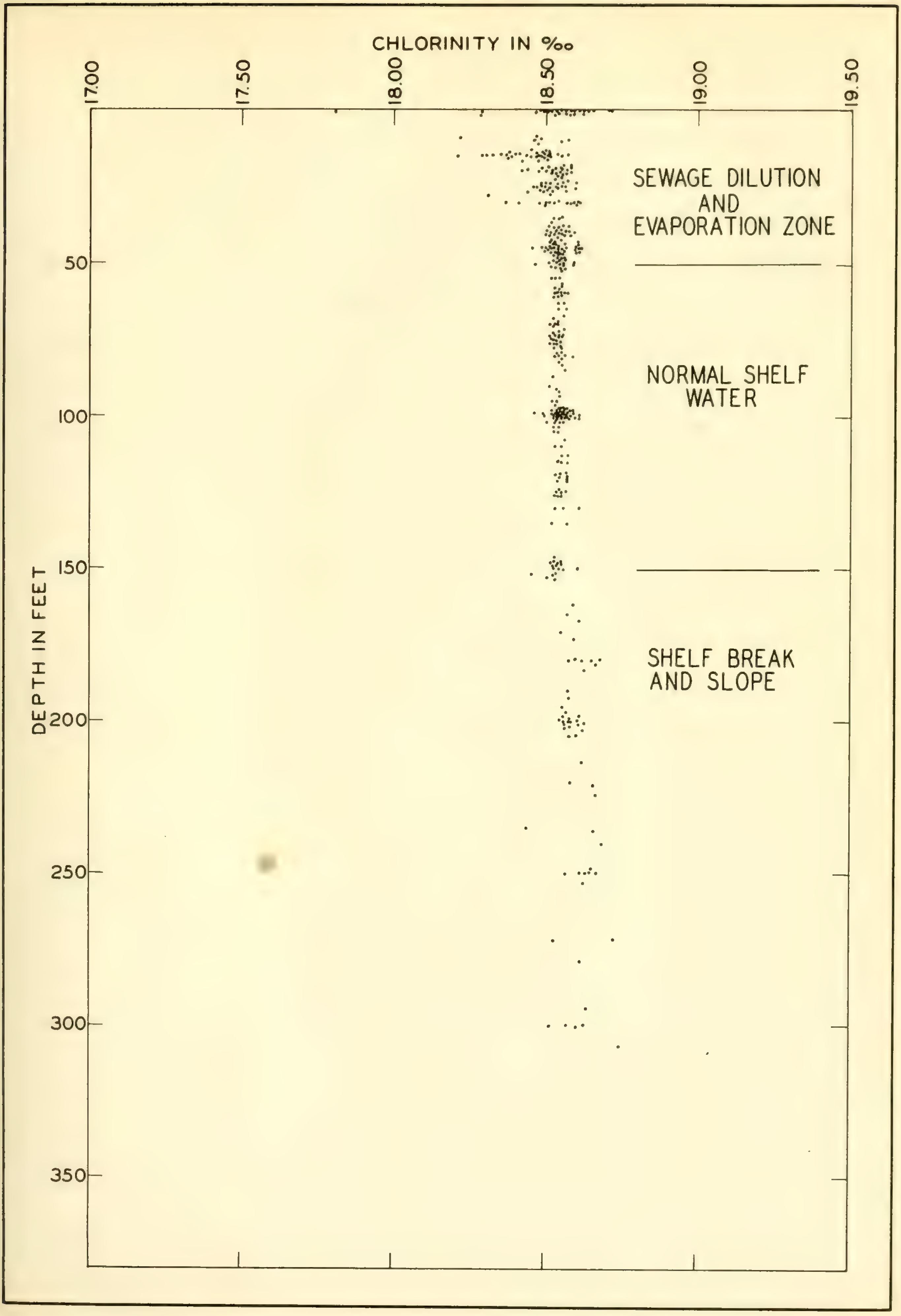
COMPARISON OF CHLORINITY TITRATIONS BY
AHF AND HYPERION TECHNICIANS

AHF Method- Knudsen titration with colorimetric end point.

Hyperion Method- Knudsen titration with potentiometric end point.

Station Number	Depth	AHF	Hyperion
3627-55	Surf.	18.55	18.49
	15'	18.55	18.49
	50'	18.54	18.48
	110'	18.53	18.46

Figure 72. Vertical salinity distribution in Santa Monica Bay, 1955-56

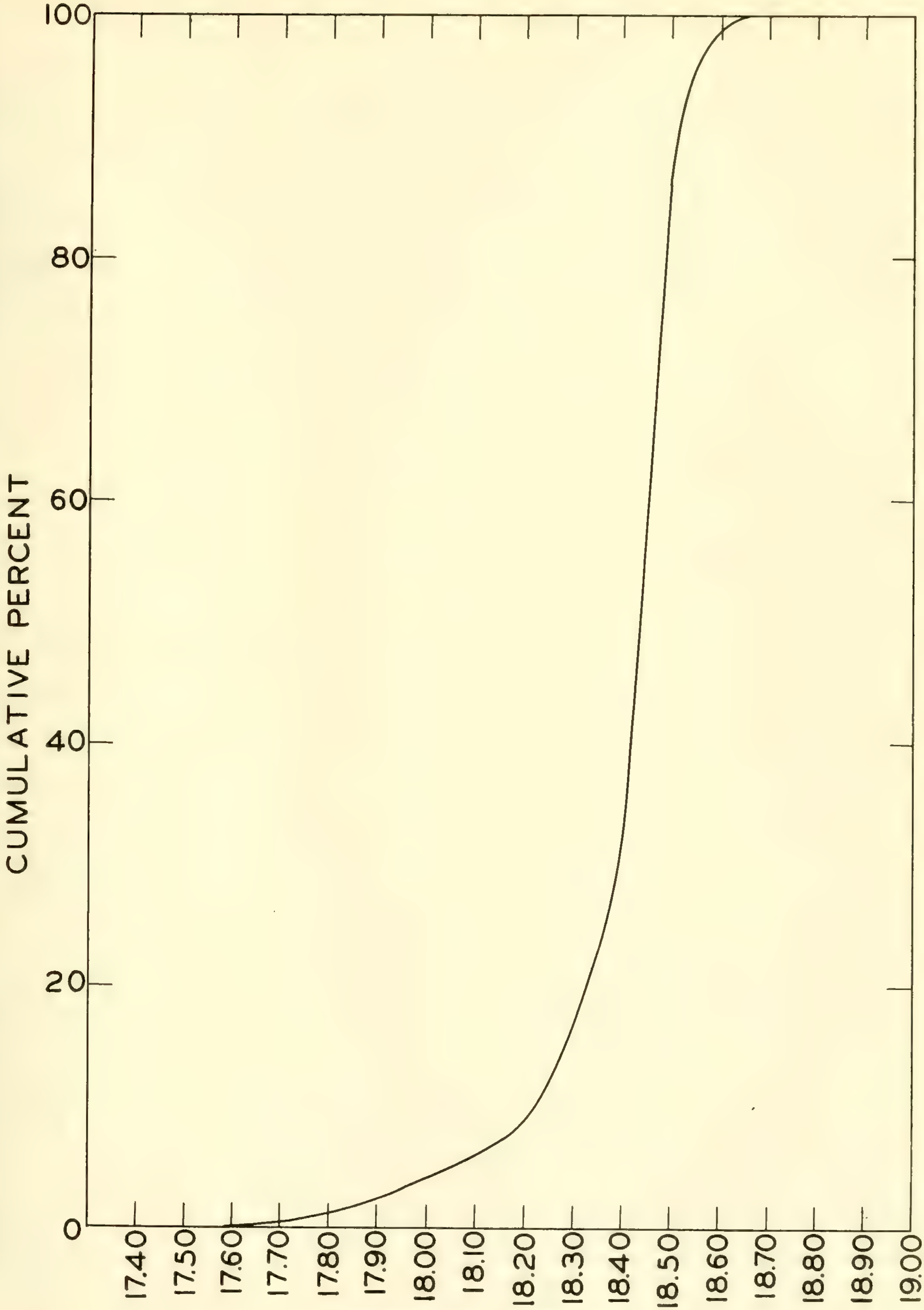


CHLORINITY IN ‰
17.00
17.50
18.00
18.50
19.00
19.50
DEPTH IN FEET
50
100
150
200
250
300
350
SEWAGE DILUTION AND EVAPORATION ZONE
NORMAL SHELF WATER
SHELF BREAK AND SLOPE

It is obvious from the diagram that the salinity (chlorinity) of the shelf water is essentially uniform from a depth of 40 feet down to the approximate break in slope at the outer edge of the shelf. The median value of 33.50 o/oo (Cl = 18.55 o/oo) has been used in all computations of dilution as the value of normal shelf water. Above a depth of 40 feet, the salinity varies over a considerable range. This variation is due to two factors. First, the effect of dilution of the normal shelf water by effluent; and second, reduction in the salinity of the surface layer by natural runoff and precipitation, and increases in salinity due to evaporation. It is obvious from an examination of the curve in Figure 73 that the highest surface salinities are still close to 33.50 o/oo (18.55 o/oo), indicating that dilution and replacement by currents rather than evaporation is the dominant factor maintaining salinities in the bay.

The overlap of points taken from samples obtained at different times of the year indicates that there is practically no seasonal variation taking place in the shelf water due to dilution or evaporation. This probably means that the water of the bay under natural conditions is entering and leaving under steady state conditions. There is no marked variation in salinity at any depth over the shelf, showing that there are no locations where water stays in place long enough to be appreciably changed by natural or man-made factors from its entering state. The uniformity of the salinity value of shelf water off the southern California coast is further shown by the identical median values for shelf water obtained off Whites Point and Orange County during the survey period. It would appear that

Figure 73. Cumulative percentage of chlorinities, Santa Monica Bay, 1955-56



100
80
60
40
20
0
CUMULATIVE PERCENT
17.40
17.50
17.60
17.70
17.80
17.90
18.00
18.10
18.20
18.30
18.40
18.50
18.60
18.70
18.80
18.90
19.00
CHLORINITY IN ‰

the shelf water is a well-mixed mass having its origins outside of the area of investigation and remaining essentially uniform along much of the southern coast due to the absence of large rivers or streams which, if present, would tend to cause a progressive dilution. The only variations are restricted to surface changes due to evaporation and dilution.

Dilution from Salinity Data

The principal area of diluted sea water in Santa Monica Bay surrounds the terminus of the Hyperion outfall. This field is the result of the mechanical diffusion of effluent into normal shelf water at depths of 40 to 60 feet at the outfall terminus, and subsequent eddy diffusion. Secondary areas of dilution occur at the mouth of Ballona Creek and at the mouths of the various creeks draining the Santa Monica Mountains during the rainy months. The water discharged from the Edison plant is shelf water and no noticeable change in salinity results. These latter areas are of little importance.

The zone that is recognizably diluted is almost always confined to the upper 10 to 20 feet of the water in the bay. It normally ranges in salinity from 31.80 o/oo to 33.42 o/oo, as is shown in Figure 72.

The Effect of Diffusers on Dilution

It has been observed during the course of the survey that effluent tends to form a column which mainly rises to, or close to, the surface. In shallow water, as at the Hyperion and Orange County outfalls, the individual ports (Hyperion) or the terminal port produces a rising turbulent column containing

fragments of water of widely differing composition. This requires that several samples be taken simultaneously in order to compute an average dilution. It has also been noted that the dilution initially produced within the column or within subsidiary columns, is similar for virtually all outfalls examined. The average dilutions range from 15 to 30 parts of sea water to one part effluent. In deeper water there are indications (Whites Point) that a slightly higher initial dilution is achieved, probably because of the greater length of the turbulent column (50 parts of sea water to one part effluent).

The dilutions were computed using the following formula:

$$X = \frac{100(Smw-Seff)}{(33.5-Seff)} = \frac{\text{parts sea water in}}{\text{100 parts mixed water}}$$

$$\text{Dilution} = \frac{X}{100-X}$$

where X is the parts sea water per 100 parts mixed water

Smw is the salinity of the mixed water

Seff is the salinity of the undiluted effluent

33.5 is the salinity of normal shelf water in parts per thousand

Dilution is the parts sea water to one part effluent.

The effluent salinity (chlorinity) can be measured at the shore end of the outfall, the mixed water salinity (chlorinity) can be measured by sampling the sewage field, and the value for normal sea water can be obtained by statistical analyses of many salinity determinations of bay water at various depths and seasons. The resulting equation is useful for computing dilutions of as much as 200 to one, depending on the errors in

determining the salinities and in choosing a value for the salinity of normal shelf water.

Extent of the Sewage Field

Figures 74 and 75 are typical representations of the sewage field, as shown by surface salinities. On both charts limits are defined by a salinity of 34.40 o/oo, representing a dilution of one part sewage to 332 parts of normal shelf water. On June 20 and August 10, 1955, the sewage field was better defined by salinity than by temperature. On June 20, the field was restricted to an area extending between Playa del Rey and Manhattan Beach and approximately 2½ miles from shore. On August 10, the effects of a northerly flow are evident, with the field occupying an area between Santa Monica and Manhattan Beach and 3½ miles from shore. Minimum salinities were encountered at the outfall, and were less than approximately 32.60 o/oo and 32.90 o/oo, respectively.

Nutrients

On January 13, 1956, and on subsequent cruises the central and northern parts of the bay were not covered, but on that date and at a point about 1½ miles off Palos Verdes Point the concentrations of silicate-silicon and phosphate-phosphorus were approximately half that present on August 16 and 17, 1955, and they showed a slight increase with depth. Nitrate-nitrogen at this time could not be detected in the surface water, but it did occur at deeper levels (2.0 µg-a/L). Only a trace of ammonia was found in the surface water, and oxygen was near saturation.

Figure 74. Surface salinity, June 20, 1955

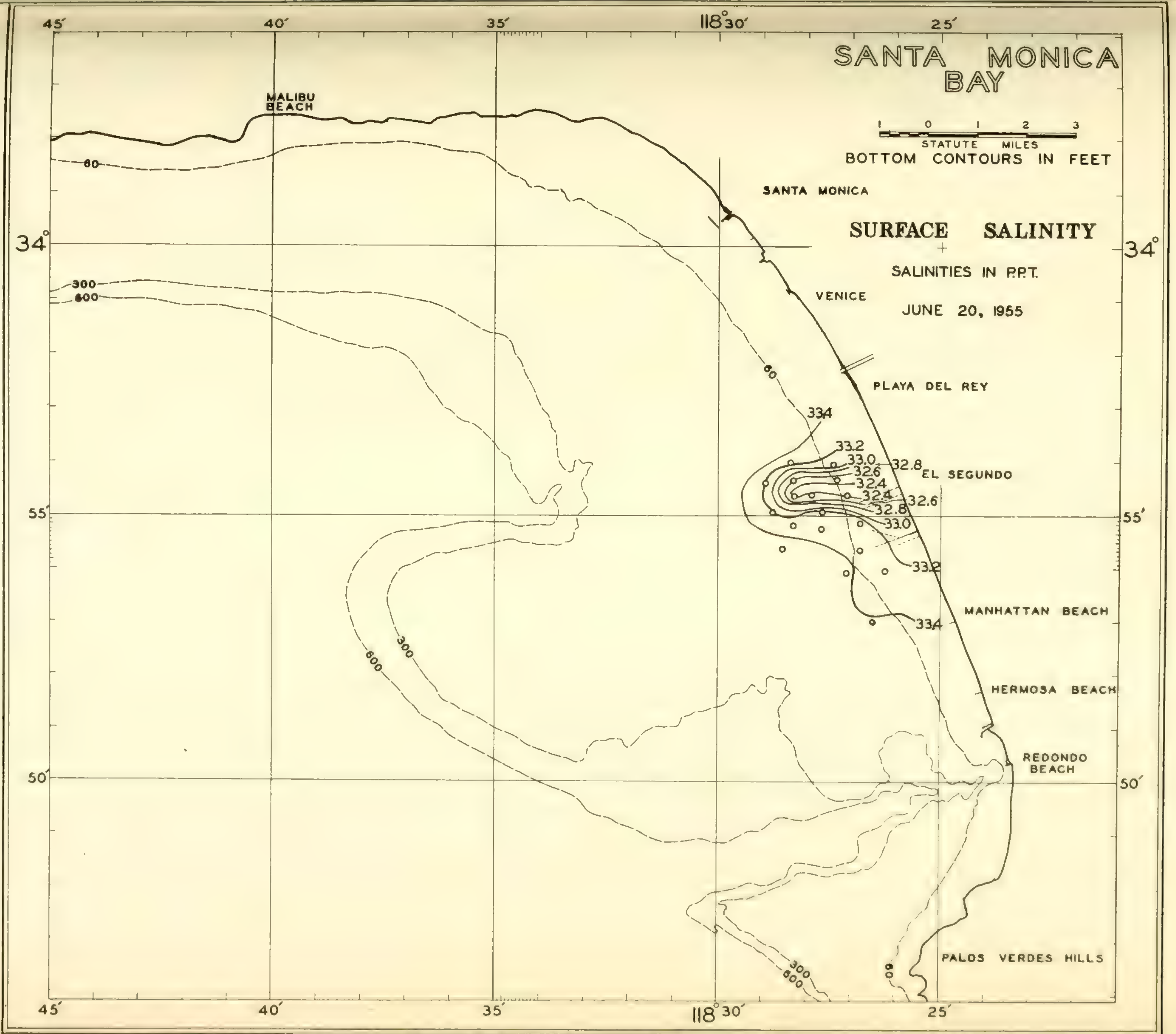
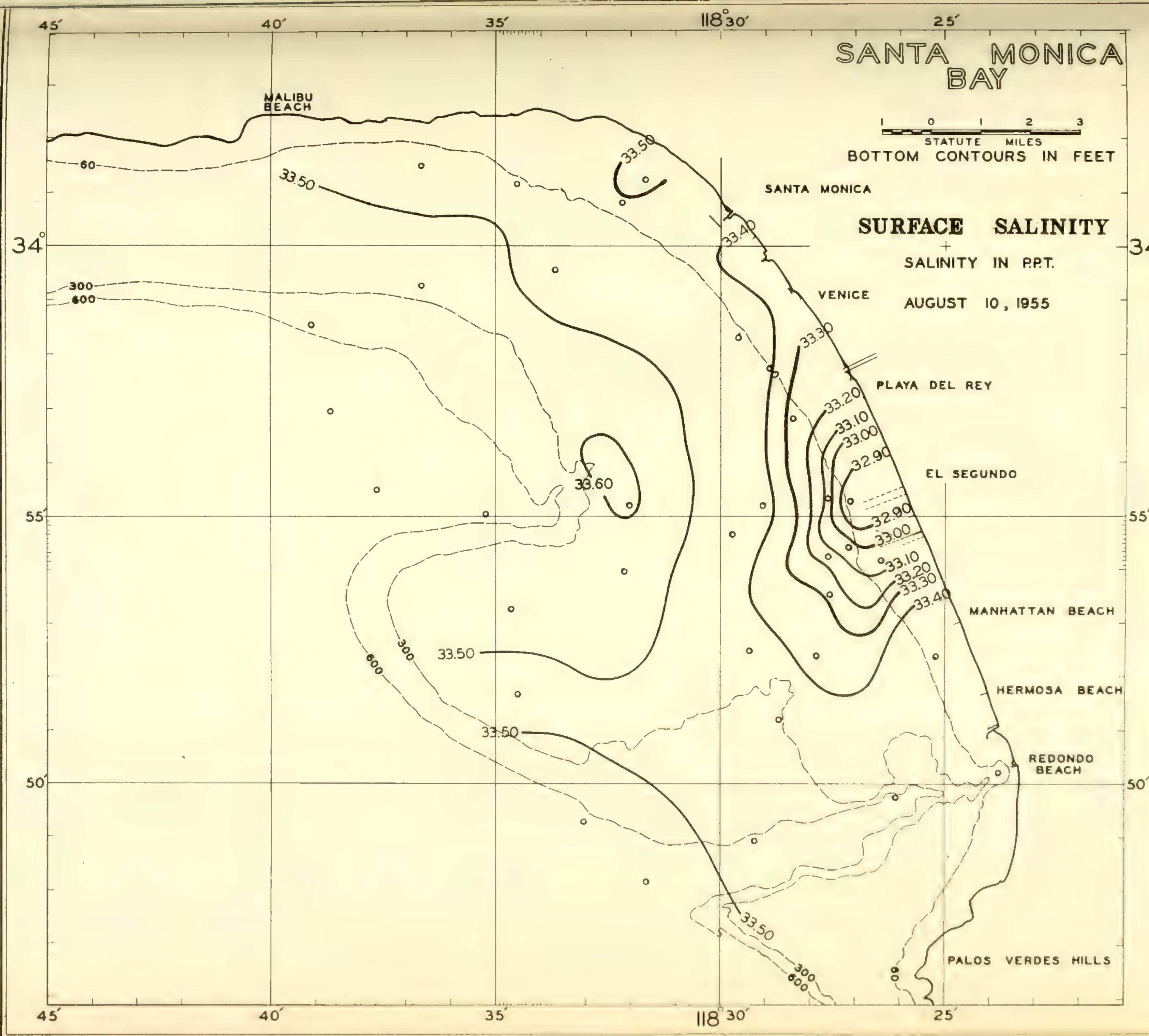

SANTA MONICA BAY
1 0 1 2 3
STATUTE MILES
BOTTOM CONTOURS IN FEET
SURFACE SALINITY
SALINITIES IN P.P.T.
JUNE 20, 1955
MALIBU BEACH
SANTA MONICA
VENICE
PLAYA DEL REY
EL SEGUNDO
MANHATTAN BEACH
HERMOSA BEACH
REDONDO BEACH
PALOS VERDES HILLS
33.4
33.2
33.0
32.8
32.6
32.4
60
300
600
45'
40'
35'
118°30'
25'
34°
55'
50'

Figure 75. Surface salinity, August 10, 1955



SANTA MONICA BAY
STATUTE MILES
BOTTOM CONTOURS IN FEET
SURFACE SALINITY
SALINITY IN P.P.T.
AUGUST 10, 1955
MALIBU BEACH
SANTA MONICA
VENICE
PLAYA DEL REY
EL SEGUNDO
MANHATTAN BEACH
HERMOSA BEACH
REDONDO BEACH
PALOS VERDES HILLS
118°30'
34°
55'
50'
45'
40'
35'
25'
33.50
33.40
33.30
33.20
33.10
33.00
32.90
33.60
60
300
600

A detailed survey in the area of Redondo Canyon on June 7 and 8, 1956, gave surface values of 0.3 μg-a/L of phosphate-phosphorus and 4.0 μg-a/L of silicate-silicon offshore. These values increased toward shore to maxima 0.5 and 6.0 μg-a/L, respectively. An attempt was made to determine ammonia, but the method was not sensitive enough to detect the small amounts present in offshore water (0 to 0.5 μg-a/L). On the north side of the head of Redondo Canyon measurable amounts (between 0.5 and 1.0 μg-a/L) began to appear. Phosphate, silicate, and oxygen values in the surface water were considerably higher than on the previous cruise in January. Throughout the area no oxygen values below 95% saturation were found, and a number of stations indicated a supersaturation of up to 7%.

Conditions at the Hyperion Outfall

In the vicinity of the Hyperion outfall the nutrient salts were concentrated considerably over the values found in surrounding shelf waters. A detailed traverse parallel to the coast was made both north and south of the boil on January 12 and 13, 1956. The dispersal pattern of the nutrients in the effluent was found to be different than at either Orange County or Whites Point. It is believed that this difference is associated with differences in oceanographic conditions and with differences in the character of the effluents. The higher concentrations of nitrate and silicate and, to a degree, phosphate were found in the subsurface and bottom layers with an intermediate layer of lower concentration at a depth of 20 feet. On the other hand, ammonia-nitrogen decreased from a relatively high value in surface water to a depth of 15 feet, where it

approached the value found in shelf water generally. South of the boil, although there was a decrease in concentration due to dilution, minor maxima occurred at 6,000 and 9,000 feet. The maximum values recorded within 3,000 feet of the boil are 23 µg-a/L for silicate-silicon, 10 µg-a/L for phosphate-phosphorus, 6.5 µg-a/L for nitrate-nitrogen, and 68 µg-a/L for ammonia-nitrogen. In comparison with the Orange County and Whites Point outfalls, Hyperion had the highest ammonia value, the lowest nitrate value, with intermediate phosphate and silicate concentrations. The oxygen concentration of the surface water was low in the boil, but to the north and the south it approached saturation within a few thousand feet. On both days large tongues of supersaturated water (up to a maximum value of 33% above the saturated value) were found in the intermediate depths and at the surface. The large increase in oxygen content above saturation values is normally attributed to phytoplankton; however, vertical net hauls in the surrounding area showed low plankton counts.

With the exception of one or two pockets of low oxygen at intermediate depth (ranging from approximately 40 to 50% of the saturated value) the area, with the exception of the boil, appears to be well oxygenated. Generally, the average oxygen values at Hyperion are higher than those of Orange County or Whites Point. An average value of 5.02 ml/L for both days was found in the surface waters of the boil, implying that there is an adequate amount of oxygen to meet the present oxidation requirements of the effluent.

Radioactive isotopes were used on the cruise on May 22, 1956, to trace the dispersion of sewage in the immediate vicinity of the Hyperion outfall. Previous to this, direct information on dilution factors around the outfall with which to compare the nutrient salts had not been available. Twenty curies of scandium 46 were injected in the sewage and on its appearance in the boil, the radioactive count was picked up by a scintillator probe over the stern of the VELERO IV and followed for the next 24 hours. At the time vertical profiles of the radioactivity were made, phosphate and ammonia determinations were also made. The limit of measurable dilution of the scandium 46 in the sewage field was 1 to 10,000. Surface samples of the station occupied in the boil on the first appearance of radioactivity gave the highest values yet found, in the area of 11.6 μg-a/L for phosphate-phosphorus and 112 μg-a/L for ammonia-nitrogen. The ammonia-nitrogen concentration is the highest recorded at any of the outfalls. The approximate dilution of the scandium at this time was 40. At a depth of 45 feet, the dilution was not measurable and the phosphate and ammonia had decreased rapidly to 0.8 μg-a/L and 4 μg-a/L, respectively.

In tracking the radioactive field, the concentrations of ammonia and phosphate did not decrease in the proportions indicated by dilutions derived from the radioactivity. This can be partly explained on the basis that the radioactive field was being mixed with water from the surrounding area, which itself contained variable and unknown quantities of nutrients. Therefore, the time rate of change in ammonia and phosphate could not be determined from the radioactive experiment.

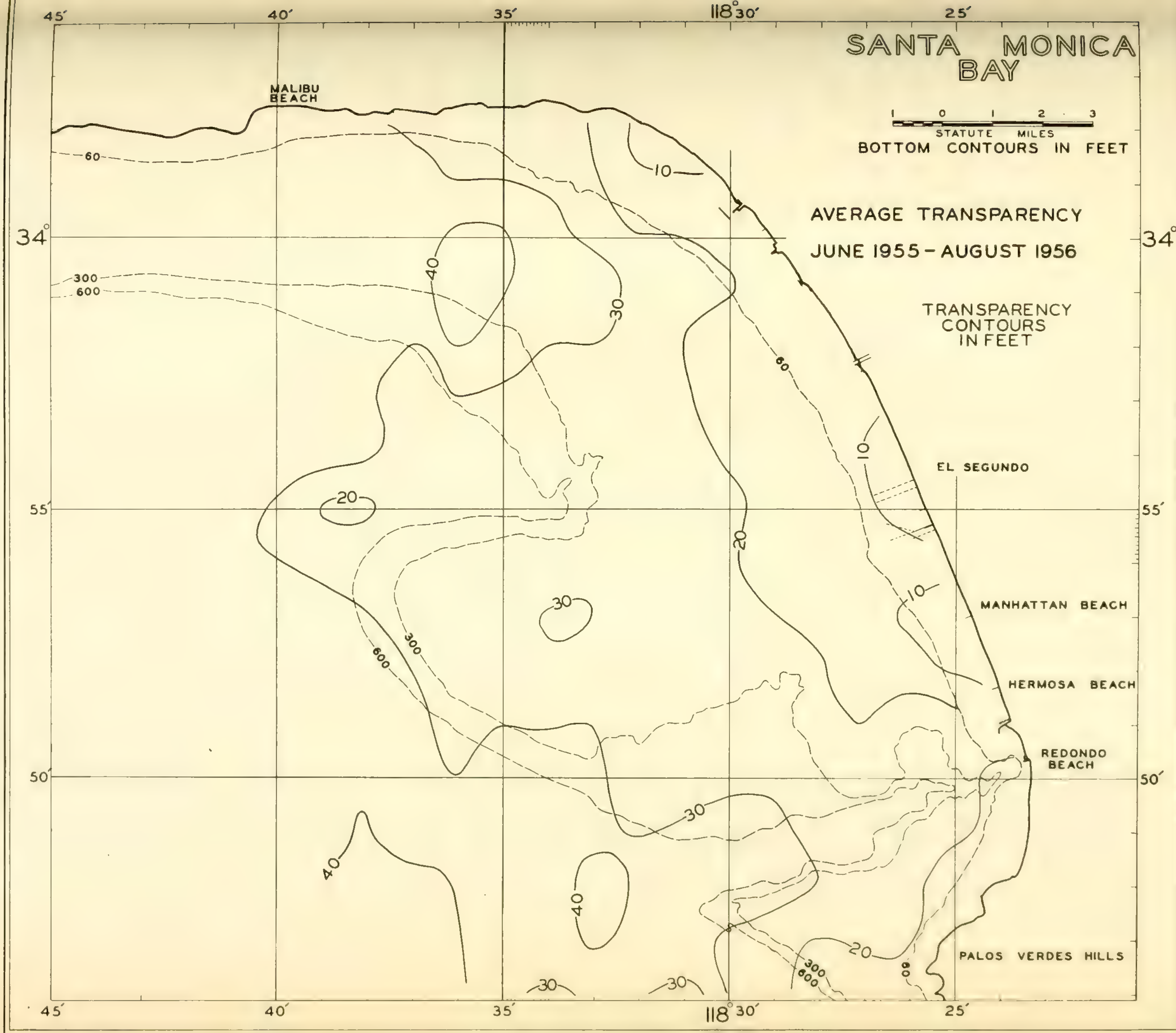
TRANSPARENCY

Methods

The transparency of the water in Santa Monica Bay was measured using both the Secchi disc and a hydrophotometer. The Secchi disc, a white metal plate 30 cm in diameter, was lowered at all hydrographic stations as a standard procedure. In 1955 and the early months of 1956, no particular concern was expressed about the transparency of the water in the bay, so that no attempt was made to determine any seasonal trends which may have existed. Although numerous readings had been obtained during the summer of 1955, the measurements taken throughout the remainder of 1955 and 1956 were scattered, and the density of the stations was not enough to allow the compilation of seasonal charts. Nevertheless, determinations of transparency in the bay taken throughout the year were in sufficient numbers to compile a composite chart of the average depth to which a Secchi disc can be seen (Fig. 76). In spite of the antiquity of the instruement and method, definite expectable patterns are apparent that show the normal offshore water conditions as well as the influence of sewage discharge.

The hydrophotometer was loaned to the Hancock Foundation by the U. S. Navy Electronics Laboratory, San Diego. It consists of a metal frame holding a light source and a receiving prism-photocell, one meter apart. The light reaching the photocell is transmitted through a waterproof cable to the deck where the electrical impulse is read in micro-amperes. In the first few feet of water light not only came from the

Figure 76. Average transparency of Santa Monica Bay, June 1955 to August 1956, based on Secchi disc.


SANTA MONICA BAY
1 0 1 2 3
STATUTE MILES
BOTTOM CONTOURS IN FEET
AVERAGE TRANSPARENCY
JUNE 1955 - AUGUST 1956
TRANSPARENCY CONTOURS IN FEET
MALIBU BEACH
EL SEGUNDO
MANHATTAN BEACH
HERMOSA BEACH
REDONDO BEACH
PALOS VERDES HILLS
118°30′
45′
40′
35′
25′
34°
55′
50′
10
20
30
40
60
300
600

electric bulb, but also from ambient light from the sun. The resultant of these two was computed against the standard calibration in air, and presented as percentage of light transmission.

The hydrophotometer was used primarily in water surrounding sewer outfalls to detect layers of debris-ladden water. Several lowerings of the device were made in Santa Monica Bay well away from the outfall, but no detailed pattern of stations was occupied (Fig. 77). Around the sewer outfalls, hydrophotometer casts were made at each bacteriological station and from the determinations of light transmission, many valuable profile patterns were produced. In Figure 78, for example, the surface portion of the sewage field can easily be recognized, as can the subsurface debris layer. In several instances the transparency profiles followed closely those plotted from bacteria samples and they were, therefore, helpful in reaching the conclusion that sedimentation of bacteria in the sea is an important factor in their disappearance.

Transparency in Santa Monica Bay

The average transparency of the water in Santa Monica Bay as measured by the Secchi disc is shown in Figure 76.. The waters within two miles of shore usually have a transparency of less than 20 feet and in the vicinity of outfalls or streams discharging detrital material into the bay, the readings are normally less than 10 feet. In deeper water and farther from shore, the transparency increases to a maximum of about 45 feet. Here the waters originate offshore and have little

Figure 77. Per cent light transmitted at depth of five feet for winter months (1955-56).

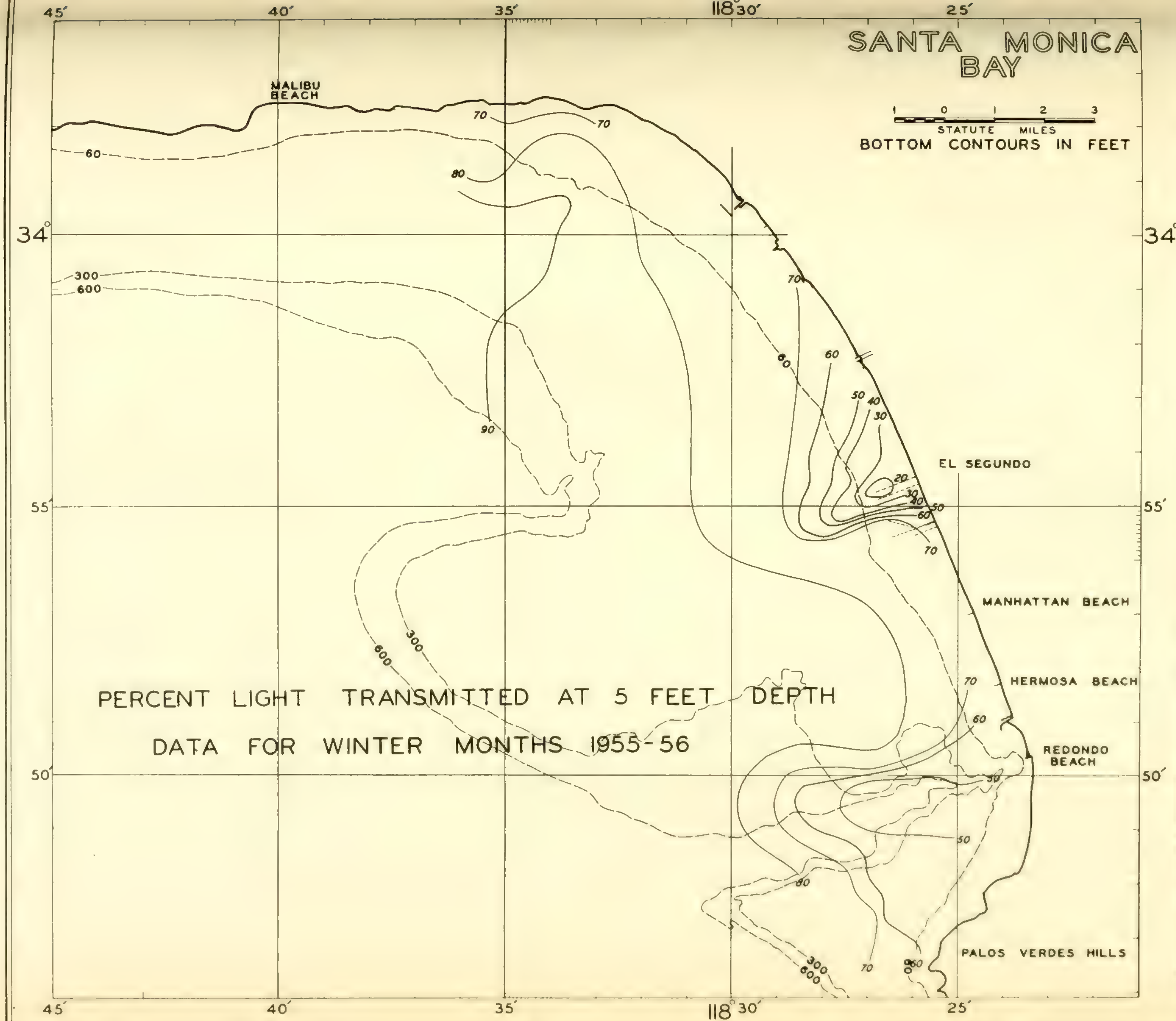
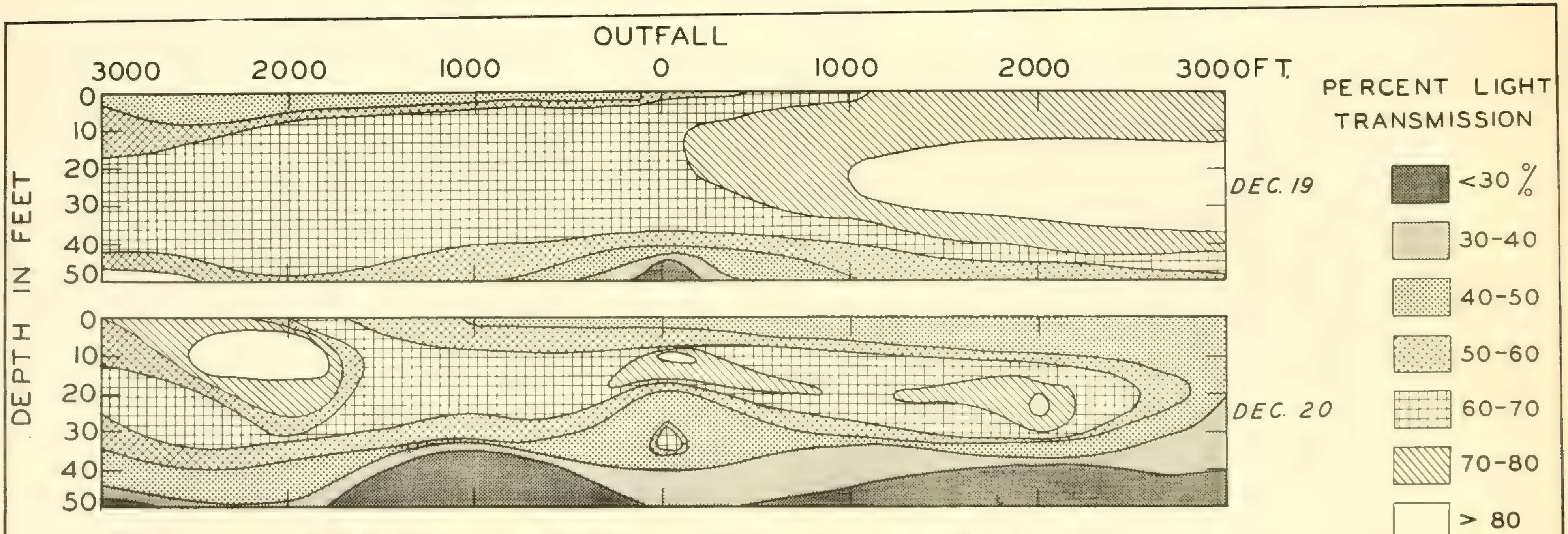

SANTA MONICA BAY
STATUTE MILES
BOTTOM CONTOURS IN FEET
PERCENT LIGHT TRANSMITTED AT 5 FEET DEPTH
DATA FOR WINTER MONTHS 1955-56
MALIBU BEACH
EL SEGUNDO
MANHATTAN BEACH
HERMOSA BEACH
REDONDO BEACH
PALOS VERDES HILLS
34°
55′
50′
45′
40′
35′
118°30′
25′

Figure 78. North-south profiles of light transmission at Orange County sewer outfall, 7000 feet offshore, December 19 and 20, 1955.



ORANGE COUNTY SEWER OUTFALL

detrital material from the land to contribute to the turbidity. There are occasions, however, when plankton or other algal blooms in the offshore area increase the turbidity to the extent that the transparency may drop to less than 20 feet. This is a normal occurrence in all coastal waters along southern California. One notes from this chart that in areas well removed from any point of sewage discharge the transparency nearshore is much lower than that offshore. This is completely normal, for along any shore bordered by a low coastal plain or by hills or mountains composed of soft shales and sandstones, as are the Palos Verdes Hills and the Santa Monica mountains, the nearshore waters are turbid to a certain extent due to silt and clay contributed by streams and kept in suspension by wave action. Thus, the direct contribution by sewage to the turbidity of the water is confined to a relatively small area in the immediate vicinity of the outfall site.

Santa Monica Bay, then, has waters that are naturally more turbid than those along the Laguna coast to the south or around Catalina Island, because of the geology of the adjacent hinterland and the nature of the circulation. Whereas along these latter shores a Secchi disc reading of 60 to 70 feet is not uncommon within a mile of shore, or closer, such transparencies have never been observed within 12 miles of shore in Santa Monica Bay. Any additional contribution of detrital or organic material into these inshore waters will, therefore, decrease the transparency to an even greater extent.

Compliance with State Standards

On May 2, 1956, the State Water Pollution Control Board established transparency standards for Santa Monica Bay which are to be conformed to "insofar as such conditions are affected by the waste discharges from Hyperion". The conditions, as stated are that, "The transparency at each sampling station (B and C), as measured by the Secchi disc, shall equal or exceed 20 feet in 50% of all readings and shall exceed 15 feet in 80% of any 20 consecutive readings." It is apparent that at the C stations in the nearshore part of the bay, this requirement cannot be met at the present time. It is also apparent that a transparency of 15-20 feet may not be met at specific times at the other C stations, nor at the B stations. This second condition, however, is not likely to be prolonged over periods great enough to constitute 50% of consecutive weekly readings. The question then arises as to whether the turbidity in the nearshore waters can be attributed to the present discharge of sewage. Analyses of the data gathered during the bacteriological work to determine the extent of the sewage field indicates that for distances greater than two miles from the outfall, the presence of sewage is undetectable from particulate material and detectable to less than 1% from chemical data. It is reasonable to assume, therefore, that turbidity resulting from the addition of particles by the sewage extends for only two, or slightly more, miles from the outfall. The low transparency of the water along the shores of the rest of Santa Monica Bay must, then, be caused by natural conditions.

In another section of this final report it has been noted that under certain conditions the addition of nutrients to the sea by the sewage may increase the number of phytoplankton in these waters by a factor of 30. The vast quantity of particulate organic material at such times may decrease the transparency to less than 5 feet. Whether this decrease in transparency caused by great numbers of plankton can be attributed directly to the sewage must, it appears, await further investigation and probably a legal decision.

Since the waters in the bay at this time do not, over protracted periods, conform to the transparency standards, it is unreasonable to assume that removing the site of the outfall from nearshore to a location 5 or more miles from shore will increase the nearshore transparency except in the immediate vicinity of the Hyperion plant. Certainly in the offshore area the transparency will be decreased markedly from its present average of 30 to 40 feet. How much the decrease will be cannot be accurately determined, but at least at the B stations along traverses 2, 3, and 4 the transparency will average less than 20 feet. It is doubtful, however, that the transparency in area 3 (1,500 feet from shore) will change from its present average, except at Hyperion. In other words, visitors to the shore will not find the water to be any less turbid than it now is, because the major portion of the turbidity is due to natural phenomena.

The Relative Merits of Transparency Instruments

The antiquity, simplicity, and obvious inherent errors in the use of the Secchi disc for the determination of the transparency of water has lead to much skepticism as to the validity of data obtained from the instrument. Many conditions other than water turbidity effect the depth to which an observer can see a Secchi disc. The amount of cloud cover, the state of the sea, the season of the year, in addition to the experience of the observer are certainly among the most important. Even so, the compilation of data gathered by the use of the Secchi disc by astute observers has yielded remarkably correlative information (Emery, 1954). Obviously, the readings cannot be considered absolute, but the relative values have been so frequently exhibited in the past three years in the nearshore areas of the Los Angeles region, that they cannot be considered to be completely aberrant. This coupled with the simplicity of operation and the ready understanding of the results by the non-scientist make it seem that the instrument may still be of some value in any marine program.

The hydrophotometer, because of the theoretical precision of its measurements, has been considered to be a much more accurate method of determining the transparency of sea water. The instrument can be calibrated, the calibration standardized, and the intensity of the light source set so that a constant reproducibility in readings may be obtained. The instrument may be lowered to any depth so that the transparency within a narrow horizontal layer can be measured with accuracy at any interval desired and reproduced under any set of sea or sky

conditions. The personal aptitude of the operator is in no way involved. On the other hand, with the instrument used during this survey, many peculiarities were encountered which could not be explained and which led to light transmission percentages that could not be rectified. There were occasions when the instrument was in obviously clear subsurface waters and values higher than those of the 100% calibration value were obtained. There were several stations occupied in sewage fields when no transmitted light was received, although ambient light was present at that depth. An instrument check showed no irregularities and subsequent lowerings repeated the performance. On other occasions, when in water with strata of sewage debris, the motion of the ship was such that wide fluctuations allowed no reasonable average reading to be obtained. Thus, despite its theoretical precision, the photometer has inherent failings which may lead to spurious results. These, coupled with the fact that the meter determines the <u>horizontal</u> transparency of discrete layers rather than the net <u>vertical</u> transparency of a water column, a factor of considerable importance when one must relate the transparency to the non-scientist, leads one to suspect the immediate value of the hydrophotometer in its present form in a monitoring program such as that required in Santa Monica Bay.

<u>A Comparison of Hydrophotometer and Secchi Disc Readings</u>

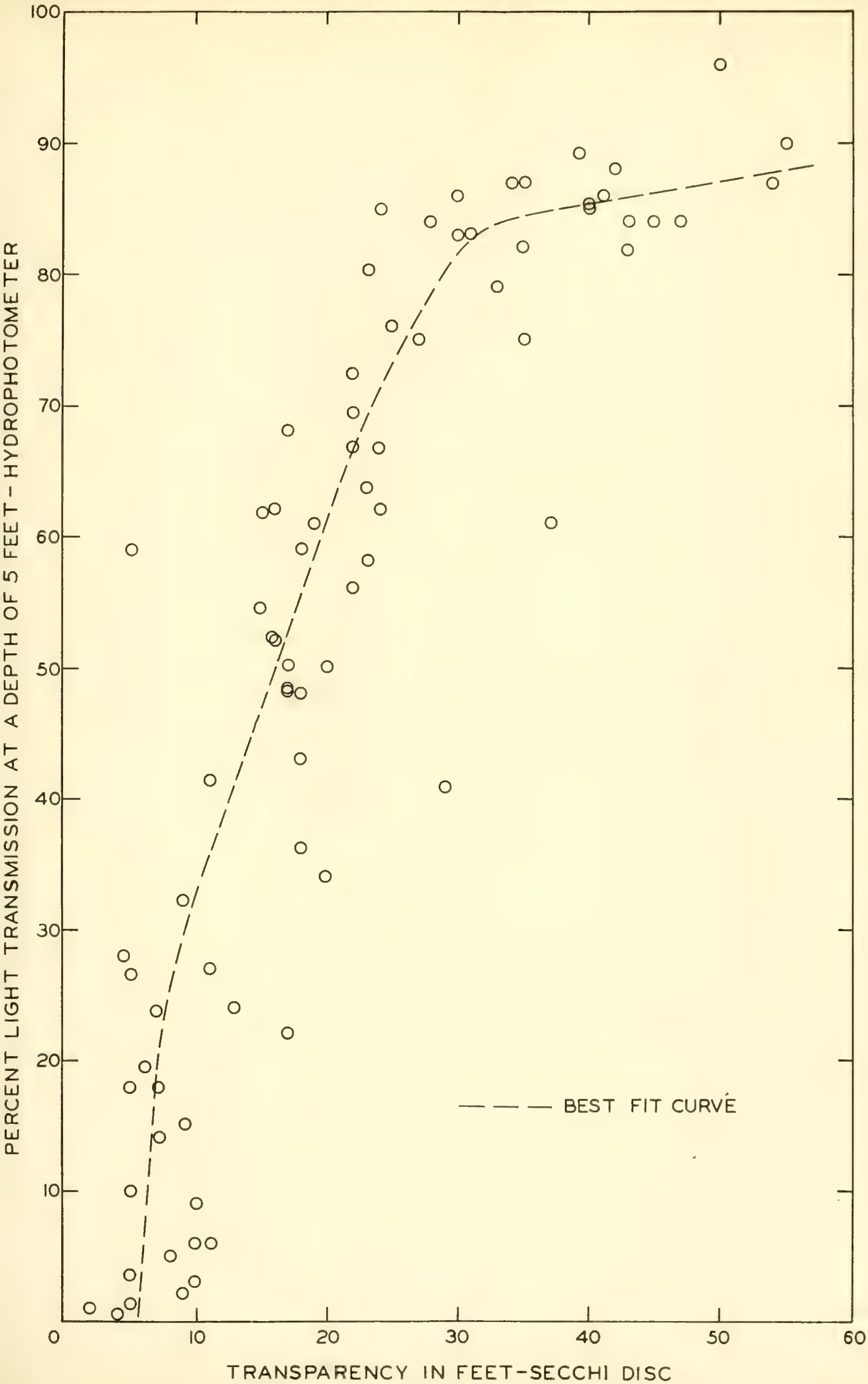
In an attempt to relate simultaneous hydrophotometer and Secchi disc readings, two graphs were drawn using the same Secchi disc readings, but different averages of those obtained

from the meter. In Figure 79, the Secchi disc depths are plotted against the per cent of light transmission at a depth of five feet. Assuming the Secchi disc readings to be accurate with the limitations imposed, and the photometer readings accurate, within their limits, then it is apparent that a low light transmission at 5 feet is effective in limiting the depth to which the Secchi disc can be seen.

In Figure 80, the average of the hydrophotometer readings at five-foot intervals to the depth of the corresponding Secchi disc is plotted against the transparency as determined by the Secchi disc. For example, if the Secchi disc was visible to a depth of 15 feet, the photometer readings at 5, 10, and 15 feet were averaged and plotted against the transparency of 15 feet. Of course, one must recognize that since the transparency of the water usually improves with depth; then if completely erroneous Secchi disc readings were taken and plotted in this method, a similar curve would result. On the other hand, one needs to assume the Secchi disc observer was competent and the readings as noted are as nearly accurate as possible. Also, one must assume that the measurements made with the meter are true, for just as there is a spread in Secchi disc readings, there is one for the hydrophotometer. With these assumptions in mind, a similar conformity to each mode of measurement as is shown in Figure 79 exists with this plot.

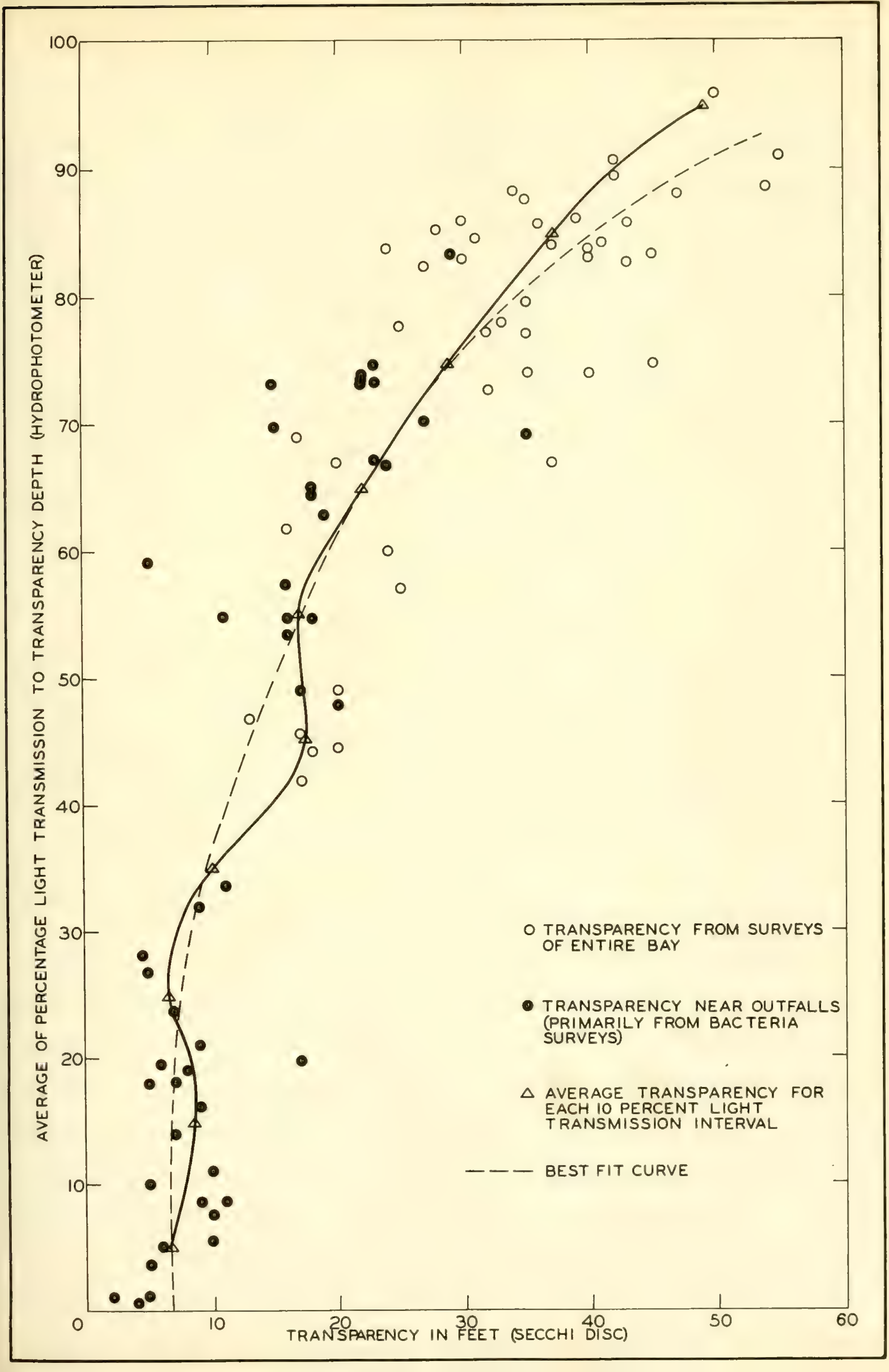
A relationship does exist, therefore, between the transparency as determined by the meter and that by the Secchi disc. In some instances the relationship is not close and without

Figure 79. Comparison of Secchi disc readings with hydrophotometer determinations of percentage light transmission at a depth of five feet.



PERCENT LIGHT TRANSMISSION AT A DEPTH OF 5 FEET - HYDROPHOTOMETER
TRANSPARENCY IN FEET-SECCHI DISC
BEST FIT CURVE
0
10
20
30
40
50
60
70
80
90
100

Figure 80. Comparison of Secchi disc readings with average light transmission to depth of Secchi disc.



AVERAGE OF PERCENTAGE LIGHT TRANSMISSION TO TRANSPARENCY DEPTH (HYDROPHOTOMETER)
TRANSPARENCY IN FEET (SECCHI DISC)
0
10
20
30
40
50
60
70
80
90
100
TRANSPARENCY FROM SURVEYS OF ENTIRE BAY
TRANSPARENCY NEAR OUTFALLS (PRIMARILY FROM BACTERIA SURVEYS)
AVERAGE TRANSPARENCY FOR EACH 10 PERCENT LIGHT TRANSMISSION INTERVAL
BEST FIT CURVE

further comparative analyses one would hesitate to say that at a light transmission figure of X, the transparency with the disc is Y. Nonetheless, there is a correspondence and it is believed that each method has a certain degree of validity.

It is recognized, however, that should a photometer be devised that measures the net vertical transparency of a water column and reduces the measurement to the distance an observer could see down into the water, it would be vastly superior to either of the instruments now available.

THE CIRCULATION OF SANTA MONICA BAY

Statement of the Problem

Of the physical factors which determine the dispersal of sewage after it has passed through an outfall into the sea, first consideration must be given to the rate and direction of transport by currents, and to the process of eddy diffusion.

It was proposed early in the survey period by members of the project staff that an investigation be made of eddy diffusion. However, in view of the complexity of the problem, it was not at all certain that within the time limit of one year a satisfactory answer could be obtained which would make it possible to forecast the dispersal of sewage from the specific outfalls under consideration. Because one major point of concern revolved about the related problem of the rate of disappearance of coliform bacteria, an intensive study was begun on the organisms themselves, the result of which are described in another section of the report of the

Hancock Foundation. The disappearance rate established included the effects of eddy diffusion, although its magnitude in relation to mortality, sedimentation, and other factors could not be determined.

Eventually, an intensive experimental and theoretical investigation into eddy diffusion in shallow or coastal water must be undertaken, because along with currents it is a physical process of the utmost importance in determining the rate of dispersal of any component of sewage, and the concentration of waste material in surrounding waters. As long as this is neglected, forecasts as to the behavior of sewage will remain largely on an empirical basis.

In the investigations of the University of Southern California the rate of disappearance of coliforms under specified conditions was determined. The next problem was to establish the direction and velocity of the ocean currents, for if the bacteria were carried ashore or in any direction at such a rate that their numbers could not be reduced to the numbers required by law, then pollution by legal definition would occur. Of course, currents are important in distributing other components of the sewage as well. During the past year the circulation of Santa Monica Bay has been measured by three methods; (1) current meters, (2) drogues, and (3) drift cards. In addition, a radioactive tracer study was conducted on May 22, 1956, from which it was hoped that additional information on the trajectory of a tagged body of water could be determined.

It had been the experience of previous investigators working in the bay that currents were generally slow, and it was widely believed that they were erratic and unpredictable. The work during the present survey has confirmed the fact that velocities are often low, but it is now evident that the currents are not erratic and random in nature; on the contrary, there are several well-defined patterns of flow. Because of the lack of basic data from other sources, it has not yet been possible to adequately investigate the causes of these patterns or to correlate their occurrence with meteorological or other conditions. In this sense only are the currents unpredictable.

Current Meter Observations

Between June 26 and October 19, 1955, 114 current meter observations were made in Santa Monica Bay using a Gemware meter at depths from 15 to 190 feet, in the following localities: the head of the Santa Monica Submarine Canyon, off the Hyperion outfall, over the rocky portion of the central shelf, off Malibu, and off Santa Monica. At many stations where subsurface and deep meter readings were taken, the surface direction and velocity was also determined by means of a current cross. On June 6, 1956, another series of 24 readings were obtained with an Ekman meter between the surface and 80 feet near the Redondo Submarine Canyon.

Velocities ranged from negligible to 0.45 statute miles per hour. (Note: all distances and velocities in this section on circulation are given in statute miles and statute miles

per hour.) Only 29 readings exceeded 0.23 MPH, and the majority were less. Many of the higher readings were obtained either in the Malibu region or in the vicinity of Redondo Canyon.

On two cruises when winds were light or absent, the direction and velocity of surface currents were obtained concurrently with 28 meter observations by means of a current cross. There are too few of these to allow any statistical treatment, but one receives the general impression that surface velocities under these conditions are from one-half to one-fourth those at 15 feet, and that the direction of flow is in much the same direction as the subsurface currents. This difference in velocities was rather unexpected, and it probably reflects errors in measuring low velocity currents by either current crosses or meters, rather than any real differences in currents themselves. Other series of surface current observations using current crosses (without concurrent meter readings) also showed, under conditions of little or no wind, velocities ranging from negligible to 0.38 MPH.

From our own results and from earlier observations by other investigators, it was evident that velocities were generally low, so low in fact that the current meters themselves probably were unreliable both as to direction and velocity (the limit of accuracy is reached somewhere between 0.1 and 0.2 MPH). While the velocities often decreased with increasing depth, there was no consistent relationship, nor were the directions obtained of much value. With one exception, the longer time-series showed no clear

tidal relationship and the directions of flow appeared to shift almost erratically. It was obvious that a program of current meter observations would yield useful information only if more accurate meters could be obtained and if a relatively elaborate program could be developed by which the entire bay would be covered at frequent intervals. The suggestion was made that self-contained, automatic recording meters be used. Even provided that their sensitivity was adequate, the problem of obtaining and installing such meters, quite aside from the time required to analyze the results, proved insurmountable within the limits of time and personnel available to the Hancock Foundation. It was therefore decided that current meter observations be curtailed.

Drogues

Early in the survey it was suggested that drogues be used, particularly to check the behavior of subsurface currents. Undoubtedly, a series of carefully planned drogue experiments would furnish much information obtainable in no other way, but here again other committments made it necessary to eliminate or severely curtail such an investigation. However, a number of drogues were tracked for periods of several hours during the period from May 4 to August 20, 1956, primarily to see if concepts of currents based upon temperature distribution in shallow water were valid.

The drift paths of the drogues are shown graphically on the charts of horizontal temperature distribution, but are summarized in Table VIII.

TABLE VIII

DRIFT OF DROGUES

Date and Location	Depth Ft.	Direction	Distance Miles	Time hr.	Velocity MPH
May 4, 1956 Between sludge & Effluent outfalls.	15	ESE	3.0	5.0	0.60
	75	SE	1.7	4.7	0.36
May 8, 1956 1 mile west of Ocean Park.	15	N	0.2	1.2	0.17
South of head Santa Monica Can.	15	E	1.6	1.5	1.07
	75	E	1.0	2.2	0.46
June 6, 1956 1/2 mi. west Hyperion	20	E	0.4	2.3	0.17
Between Sludge & effluent outfalls	20	E	1.1	2.5	0.44
	85	E	1.1	2.5	0.44
June 11, 1956 Off Hyperion	15	S	1.1	3.0	0.37
	35	E 1/4 mi then S	0.45	2.7	0.17
June 28, 1956 Effluent outfall	15	ENE	2.9	5.9	0.49
	75	ENE	1.1	5.2	0.21
3 mi. S eff. out.	15	ENE	1.3	5.0	0.26
July 27, 1956 Sludge outfall	15	SE	0.4	1.3	0.31
Effluent outfall	15	SSE	2.1	6.8	0.31
	75	SSE	0.8	4.2	0.21
August 10, 1956 Sludge outfall	40	E	0.4	1.0	0.40
Effluent outfall	30	ESE	2.5	5.5	0.45
	90	SE	1.4	5.25	0.28
August 21, 1956 Sludge outfall	50	E	0.2	0.75	0.27
Effluent outfall	15	NE	1.4	5.7	0.25
	80	NNE	1.8	5.5	0.32

In general, velocities were somewhat greater than those obtained from drift cards. This is to be expected because the drogues were observed only over a period of a few hours and usually when onshore winds were blowing, while the drift of cards was a net motion reflecting to some extent opposing land and sea breezes, and tidal and other current action. These limited observations showed no correlation in either direction or velocity with the stage of the tide or with its ebb and flow.

In seven instances, shallow and and deep drogues were released simultanteously over the shelf, but in only one did the two drogues move with approximately equal velocities. In one case (August 21) the deep drogue moved faster than the shallow one. In all others the speed of the deeper drogue was about half that of the shallow one. Moreover, both shallow and deep drogues travelled in approximately the same direction, which can be seen from Table IX.

On June 11, two drogues were released just off the Hyperion outfall, one at 15 feet and one at 35 feet below the surface. In this case the surface drogue drifted south and parallel to the shore for two hours, while the deep drogue in one and one-half hours drifted directly shoreward and ended its course above the end of the Hyperion outfall.

Drift Card Results

Introduction

As a means of determining the drift of surface currents in this area, drift cards have proved to be highly successful. Except for a few localities in the northern and southern ends

TABLE IX

RELATIVE ANGLE OF DRIFT BETWEEN
DEEP AND SHALLOW DROGUES

Date 1956	Depth of drogues (feet)	Relative Angle
May 4	15 & 75	25° right
May 8	15 & 75	less than 5°
June 6	20 & 85	less than 5°
June 28	15 & 75	less than 5°
July 27	15 & 75	less than 5°
Aug. 10	30 & 90	20° left
Aug. 21	15 & 80	20° left

of the bay, the beaches are well populated in summer and surprisingly so during the winter months when there seems to be scarcely a stretch of beach that does not have a few strollers each day. Because of this and the fact that the currents were frequently directed toward shore, the percentage of recoveries was high. In all, 5,236 cards were released during the year, and 1,803, or 34% have been recovered. Returns from the last two cruises, August 9 and 10 and August 20 and 21, are still incomplete.

Fourteen cruises were made beginning September 9, 1955, and ending August 21, 1956. Twelve of these were made along a series of six lines each about two miles apart, and extending out from the beach to a distance of approximately seven miles. There were three stations on each line, one at three, one at five, and another at seven miles from shore. The position of two stations was adjusted so that they fell at the approximate locations of the proposed sludge and effluent outfall terminals. In addition to these 18 stations, one was usually included in the southern inshore portion of the bay. The other two cruises involved only a few stations each and were made incidentally in connection with other field work. A typical example of the stations and the area covered by the regular cruises is shown in Figure 81, p. 182.

The drift cards used in this survey consisted of two red-striped labels, a self-addressed prepaid return envelope, and a letter requesting information on location, date, and time of recovery. These were enclosed in a transparent plastic envelope. The envelope was made of polyvinyl flat seamless

tubing, 4 5/8 by 10 inches, which was heat sealed at both ends. Two 5/8 inch cut steel washers were included to provide ballast so that the card floated upright in the water with a minimum of surface exposed to the direct effects of the wind. Assembly of the cards was done by a commercial packaging concern. Because experiments showed that the amount of air entrapped in the plastic cover was variable and was often not sufficient to allow the drift card to remain afloat, a soda-straw was inserted at the time of assembly to insure that enough air was present to float the card.

During preliminary experimental design of the cards, as well as on the first two cruises (September 8 and 29), a few unweighted cards were used. These remained flat on the surface of the water and were driven at considerable velocity directly downwind. At the time, neither the effects of the wind on the immediate water surface nor on the possible drift of surface films were being considered, and the use of unweighted cards was abandoned. Now, however, considering the difficulty of obtaining reliable wind data in this area and because of the possible importance of knowing the drift of "grease balls" and other low density components of sewage, we would recommend that if other surveys are undertaken in the future, a certain percentage of unweighted cards be released at all stations as a matter of routine. On the cruises in Santa Monica Bay, too few of the unweighted cards were released and later recovered to justify any conclusions as to differential drift.

It is believed that the drift cards reflected with a reasonable degree of accuracy the direction and velocity of the upper foot or two of water. To some unknown extent they are directly influenced by the wind. While the magnitude of this error is not known, it seems reasonable to assume that over short periods of time, during the 1 to 3 days required for many of the cards to reach the beach, and during the periods of relatively low wind velocities which were present following most cruises, they were not deflected enough to invalidate the general conclusions which have been drawn from their drift.

One annoying occurrence was that obvious errors in date of recovery were made by those returning the cards. Perhaps this was to be expected, especially since many of the returns were made by children. Such errors were difficult to eliminate, because at some stations returns were spread out over many days and there was no valid basis on which to decide whether or not any early find was actually made on the date recorded. Consequently, all cards were accepted at their face value except a few which gave quite impossible velocities, even negative ones. It is for this reason that the highest velocities described for each cruise may sometimes be open to question. In general, however, high velocities at any one station were supported by more than one card or by similar velocities from adjacent stations and the general picture, therefore, is unchanged.

The drift card cruises were scheduled at more or less regular intervals, and because of the nature of the whole

program, no attempt was made to distribute them according to selected weather conditions. Except for the fact that no cruises were conducted during the passage of major weather disturbances, the coverage of the bay as a whole and of the different seasons, probably gives a reasonable picture of conditions during the 1955-56 season. It is to be expected that during periods of strong westerly winds the surface water may be driven toward shore. Whether or not this is always true of the main mass of water is not certain. It has been observed by the lay of the ship at anchor in various parts of the bay, as well as by drogues at a depth of 15 feet and by current meters at various depths, that waters within a distance of 5 miles from shore frequently take a direction at a considerable angle or even directly opposed to the wind, even though that wind may have been blowing for many hours. By the inherent limitations of the survey, this and many other fundamental questions relating to winds, waves, and currents remain yet to be investigated.

On the earlier cruises, drift cards were released during the course of an ordinary day's work, usually between about 9 a.m. and 3 p.m. From some stations cards were recovered during the early morning hours on subsequent days. This was of little consequence as long as velocities were low and the currents were not directed toward the neighboring beaches. However, on the February, March, and April cruises, there was a consistent shoreward pattern of currents as well as an increase in velocities. When it was apparent that a time of drift for bacteria of less than 24 hours might be critical,

from the standpoint of meeting pollution standards at the beach, it also became apparent that there was a possible gap in recoveries during the important interval of from 8 to 22 hours after releasing the cards. Accordingly, on the cruises of May 23, July 26, August 9, and August 20, 1956, cards were dropped between about 9 p.m. and 3 a.m. This procedure made it possible to recover cards should they wash ashore during the critical interval. In no instance was a card recovered early the following morning from a sludge or effluent station. This fact increases the reliability of computations of maximum drift velocities from those stations.

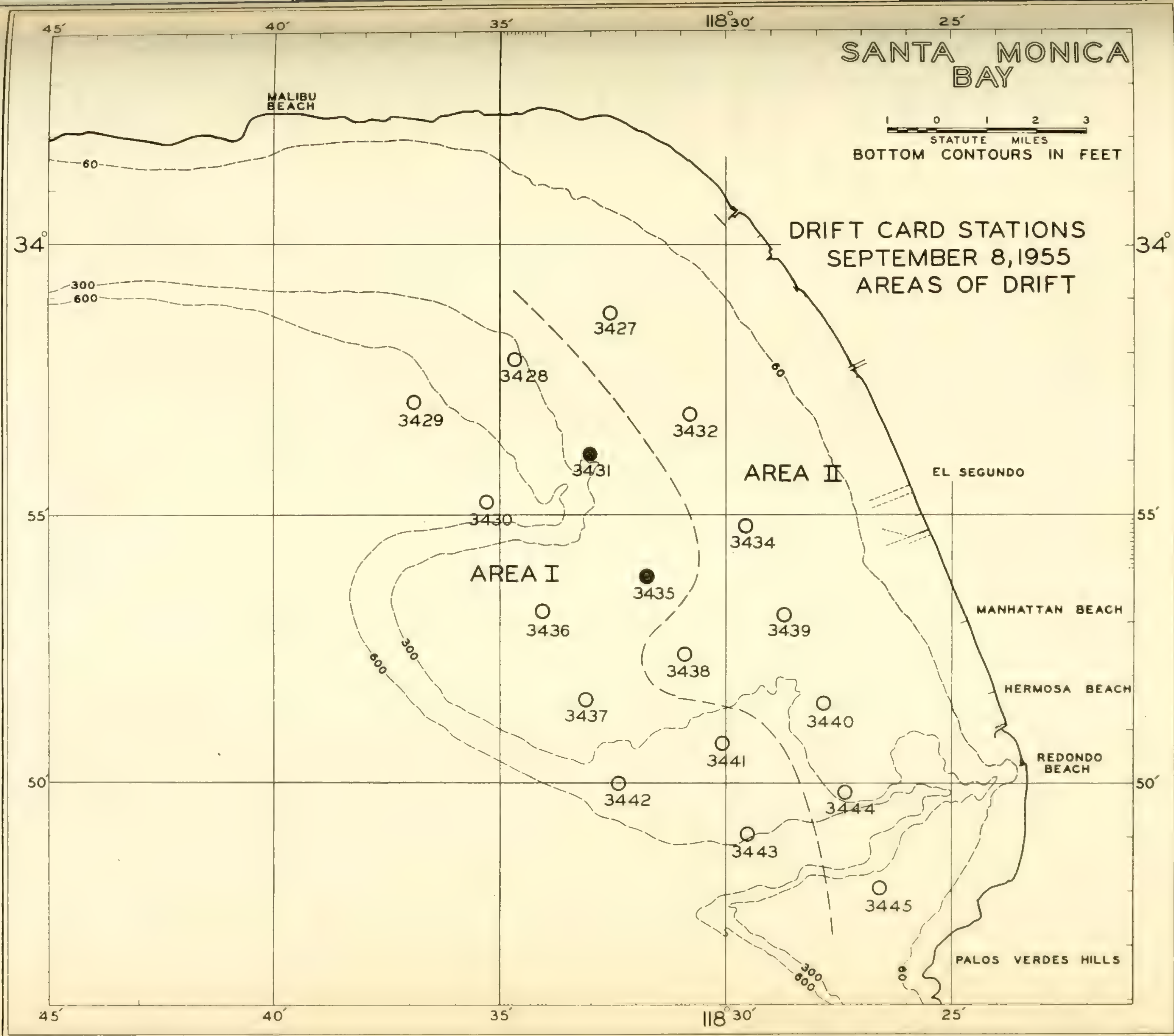
Explanation of Drift Card Charts

The distribution of stations over the bay on most cruises was similar to that on September 8, 1955 (Fig. 81). Station charts for individual cruises, therefore, are presented only when special conditions require their being included.

Stations located at or near the proposed outfall terminals are indicated by solid circles; all other stations are indicated by open circles.

On charts showing the returns of drift cards, the station number and the number of returns over the number released (i.e., 6/25) are written immediately below each point of release. Lines representing assumed paths or directions of flow from individual stations or from groups of stations are drawn. Whenever two sets of figures are written at the ends of the arrows or along the flow lines, the first indicates the travel time in days (unless otherwise indicated) and those in parentheses give the number of cards recovered at each locality. Whenever

Figure 81. Drift card stations, September 8, 1955


SANTA MONICA BAY
STATUTE MILES
1 0 1 2 3
BOTTOM CONTOURS IN FEET
DRIFT CARD STATIONS
SEPTEMBER 8, 1955
AREAS OF DRIFT
MALIBU BEACH
EL SEGUNDO
MANHATTAN BEACH
HERMOSA BEACH
REDONDO BEACH
PALOS VERDES HILLS
AREA I
AREA II
3427
3428
3429
3430
3431
3432
3434
3435
3436
3437
3438
3439
3440
3441
3442
3443
3444
3445
60
300
600
45′
40′
35′
118°30′
25′
34°
55′
50′

two figures are given for travel time, the first figure in all cases is the minimum time. The second figure is not always the maximum, but represents the highest significant travel time, for it would be misleading to include additional figures for cards whose recovery was obviously delayed for reasons not directly associated with the currents themselves.

Cruise of September 8, 1955

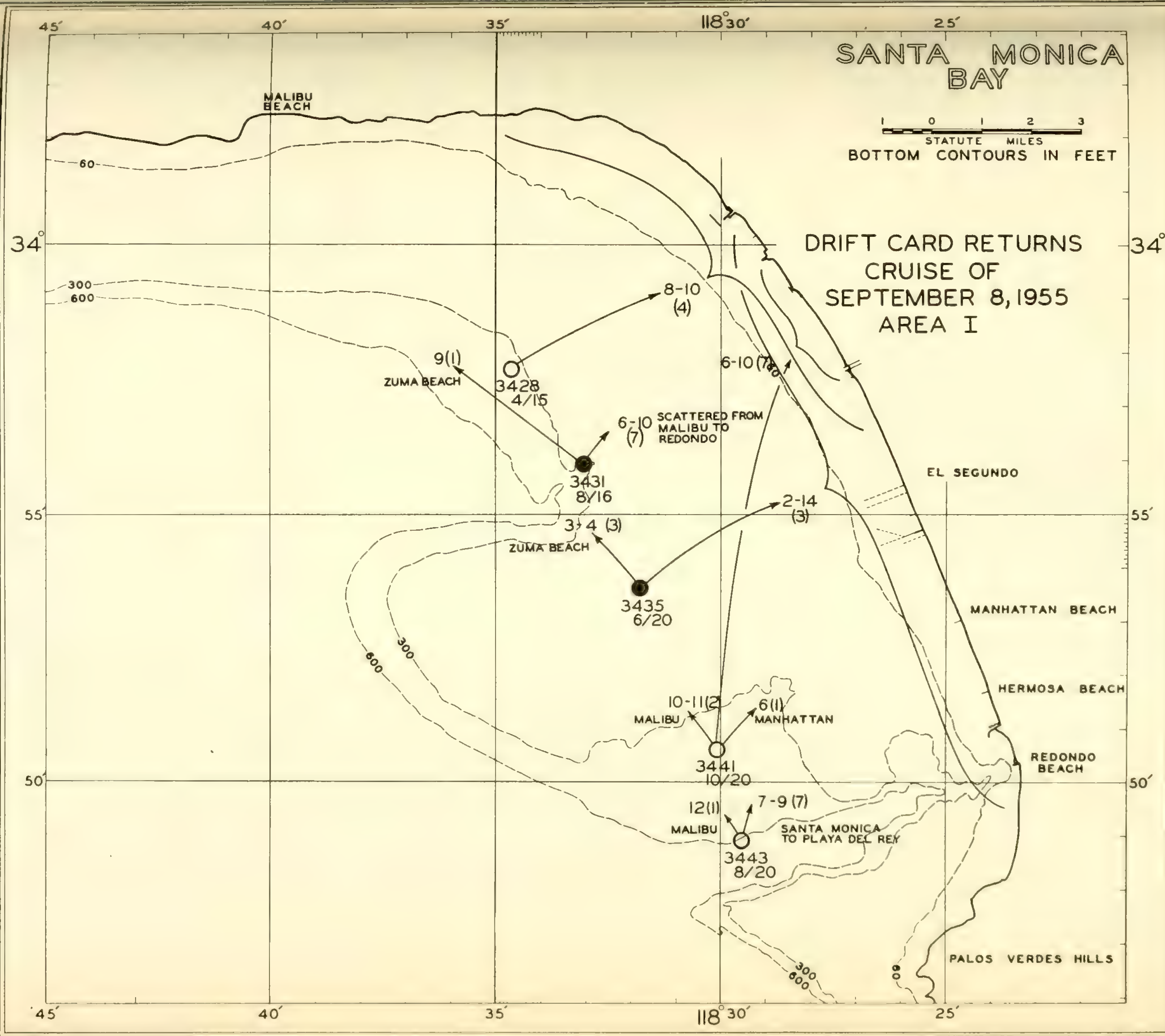
When returns from the first drift card cruise were plotted, it was obvious that the cards released within 3 miles of shore behaved in a manner quite different than those from the 5- and 7-mile stations. Accordingly, the region has been divided into Areas I and II (Fig. 81). Area I is the more offshore and Area II the more inshore portion of the bay.

Points of release and recovery of cards from Area I are shown in Figures 82 and 83. Most of these cards drifted for a relatively long time, 5 days to 3 weeks, before they were recovered on beaches which, at this time of the year, were still well populated by late-season swimmers. Conclusions as to the early paths of flow from these stations might be uncertain were it not for a few cards which were picked up only 2 to 4 days after release. A detailed time-sequence of recoveries of cards from Area I indicate a current which flowed north along the central coast and then west past Malibu, depositing a few cards along the shore as it went. However, the path of flow after leaving the vicinity of Point Dume is uncertain. After many days, the cards, now widely scattered, drifted back into the region between Zuma Beach on the north and Palos Verdes on the south. One card appears

Figure 82. Drift card returns, September 8, 1955 Area I.


SANTA MONICA BAY
STATUTE MILES
BOTTOM CONTOURS IN FEET
DRIFT CARD RETURNS
CRUISE OF
SEPTEMBER 8,1955
AREA I
MALIBU BEACH
EL SEGUNDO
MANHATTAN BEACH
HERMOSA BEACH
REDONDO BEACH
PALOS VERDES HILLS
3429 8/13
5-16 (8) SCATTERED FROM MALIBU TO PLAYA DEL REY
3430 8/12
5-9 (8) FROM SANTA MONICA TO REDONDO
3436 7/20
6-15 (4) FROM SANTA MONICA TO PLAYA DEL REY
10-14 (2) PT. VICENTE TO ALAMITOS BAY
3437 8/19
6-23(8) FROM MALIBU TO REDONDO
15(1) MALIBU
3442 9/20
6-24 (8) FROM EL SEGUNDO TO PORTUGUESE BEND
118°30′
34°
55′
50′
45′
40′
35′
25′
60
300
600

Figure 83. Drift card returns, September 8, 1955
Area I.


SANTA MONICA
BAY
1 0 1 2 3
STATUTE MILES
BOTTOM CONTOURS IN FEET
DRIFT CARD RETURNS
CRUISE OF
SEPTEMBER 8, 1955
AREA I
MALIBU BEACH
ZUMA BEACH
EL SEGUNDO
MANHATTAN BEACH
HERMOSA BEACH
REDONDO BEACH
PALOS VERDES HILLS
3428
4/15
8-10
(4)
9(1)
3431
8/16
6-10
(7)
SCATTERED FROM MALIBU TO REDONDO
3435
6/20
2-14
(3)
3-4 (3)
3441
10/20
10-11(2)
MALIBU
6(1)
MANHATTAN
3443
8/20
12(1)
7-9 (7)
SANTA MONICA TO PLAYA DEL REY
60
300
600
34°
55′
50′
45′
40′
35′
118°30′
25′

to have escaped the bay on its voyage and drifted out through the San Pedro Channel. It was recovered at Alamitos Bay two weeks after it had been released. Whether the cards were trapped in a large counter-clockwise gyral extending well outside the bay, or simply drifted about for a time offshore and then were carried eastward by a reversal in current direction, is not known.

Inspection of Figures 84 and 85 shows that in Area II a well-defined current flowed to the north in the inshore region. At least a portion of this current rounded Point Dume and four cards were deposited near Zuma Beach. Two cards, one from Station 3427 and one from Station 3434 came ashore near Redondo after 10 to 12 days. These may have been carried along with cards from Area I and returned to the bay only after a relatively long journey.

A total of 334 cards were released, and 145 returned (42%). Current velocities were generally low, of the order of 6 miles per day (0.25 MPH) or less.

Cruise of September 29, 1955

An entirely different current pattern existed three weeks later. The only similarity to the September 8 cruise was that the bay could likewise be divided into areas, in this case three, depending upon the behavior of the cards released (Fig. 86).

Area I lay offshore and included all of the 7-mile stations but one, and two 5-mile stations in the southern sector. From this area all recoveries without exception were made to the south and outside the bay. These recoveries are shown in

Figure 84. Drift card returns, September 8, 1955
Area II.

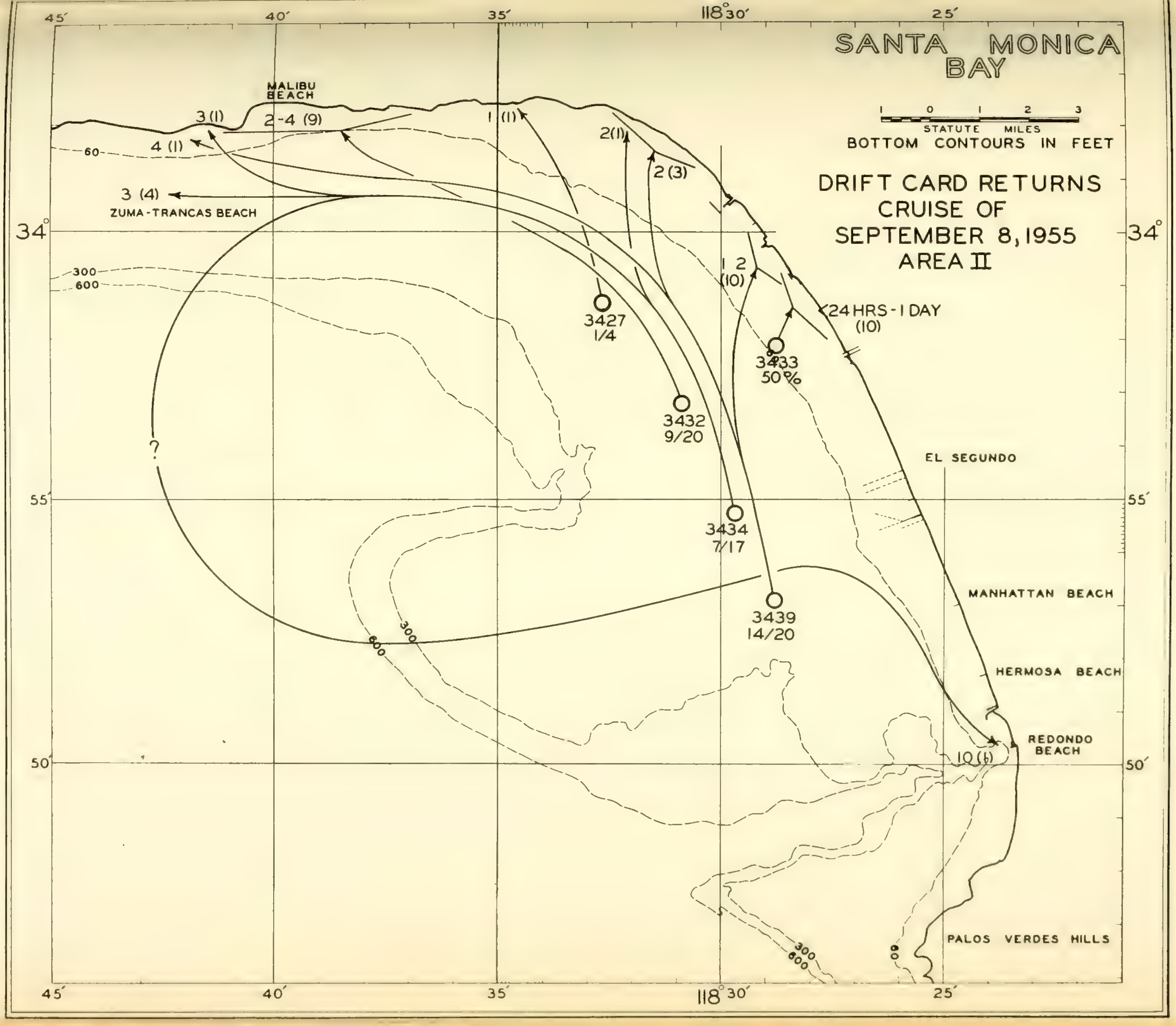
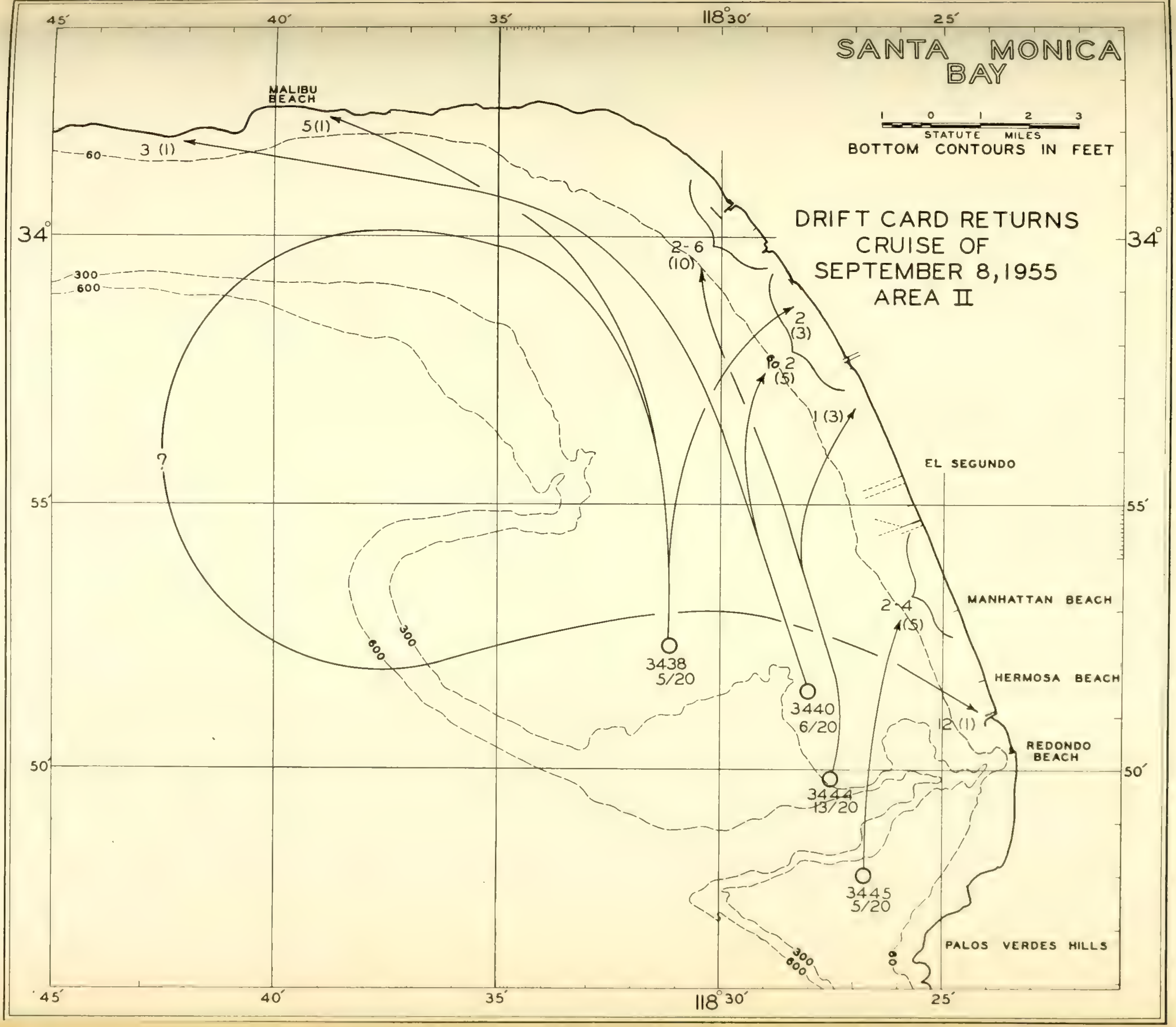

SANTA MONICA BAY
STATUTE MILES
BOTTOM CONTOURS IN FEET
DRIFT CARD RETURNS
CRUISE OF
SEPTEMBER 8, 1955
AREA II
MALIBU BEACH
3 (1)
2-4 (9)
1 (1)
2(1)
2 (3)
4 (1)
3 (4)
ZUMA-TRANCAS BEACH
1 2
(10)
24 HRS - 1 DAY
(10)
3427
1/4
3433
50%
3432
9/20
3434
7/17
3439
14/20
EL SEGUNDO
MANHATTAN BEACH
HERMOSA BEACH
REDONDO BEACH
10 (1)
PALOS VERDES HILLS
60
300
600
?
45′
40′
35′
118°30′
25′
34°
55′
50′

Figure 85. Drift card returns, September 8, 1955
Area II.



SANTA MONICA BAY
STATUTE MILES
BOTTOM CONTOURS IN FEET
DRIFT CARD RETURNS
CRUISE OF
SEPTEMBER 8, 1955
AREA II
MALIBU BEACH
EL SEGUNDO
MANHATTAN BEACH
HERMOSA BEACH
REDONDO BEACH
PALOS VERDES HILLS
3438
5/20
3440
6/20
3444
13/20
3445
5/20
3 (1)
5(1)
2-6
(10)
2
(3)
to 2
(5)
1 (3)
2-4
(5)
12 (1)
?
60
300
600
34°
55′
50′
45′
40′
35′
118°30′
25′

Figure 85. Drift card returns, September 8, 1955
Area II.

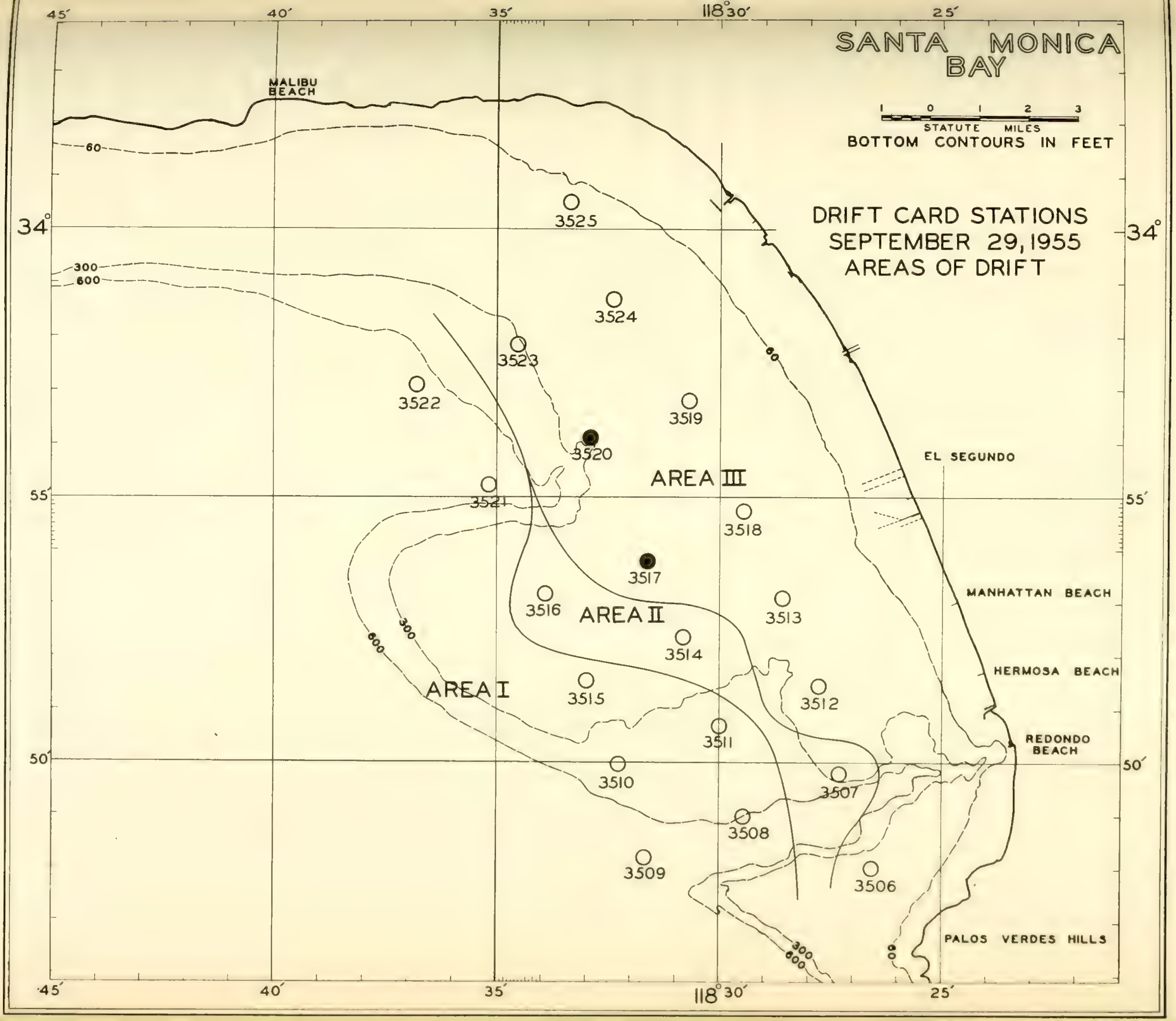
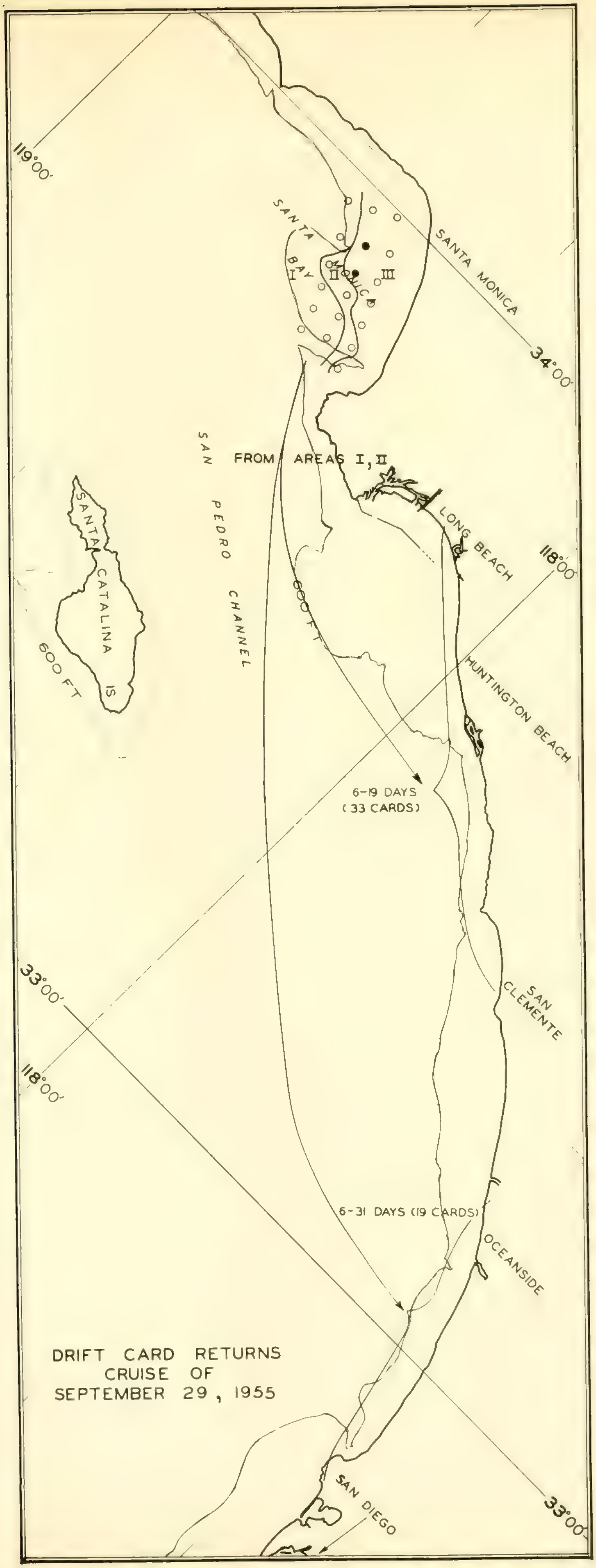

SANTA MONICA BAY
STATUTE MILES
BOTTOM CONTOURS IN FEET
DRIFT CARD STATIONS
SEPTEMBER 29, 1955
AREAS OF DRIFT
MALIBU BEACH
EL SEGUNDO
MANHATTAN BEACH
HERMOSA BEACH
REDONDO BEACH
PALOS VERDES HILLS
AREA I
AREA II
AREA III
3506
3507
3508
3509
3510
3511
3512
3513
3514
3515
3516
3517
3518
3519
3520
3521
3522
3523
3524
3525
60
300
600
34°
55′
50′
45′
40′
35′
118°30′
25′

Figure 87, together with those from Area II which drifted outside the bay. Of the 140 cards released in Area I, 45 (32%) were recovered 6 to 31 days later along the southern California coast between Long Beach and Pacific Beach (San Diego).

Area II (Fig. 88) is an intermediate one consisting of three stations in the central and southern half of the bay, from which cards were recovered both inside and outside of the bay. Although substantial numbers, 23% of the cards released in this area, were scattered between Huntington Beach and La Jolla, an equal number were picked up on the beaches of Santa Monica Bay mostly between Manhattan and Malaga Cove. Cards recovered in the bay indicate a southerly component to the inshore drift and maximum velocities of about 6 miles per day (0.25 MPH). There were two recoveries at Venice from Station 3516. These are not necessarily related to a diverging current in the inshore area because the time of drift was long (9 days) and the actual trajectory cannot be determined.

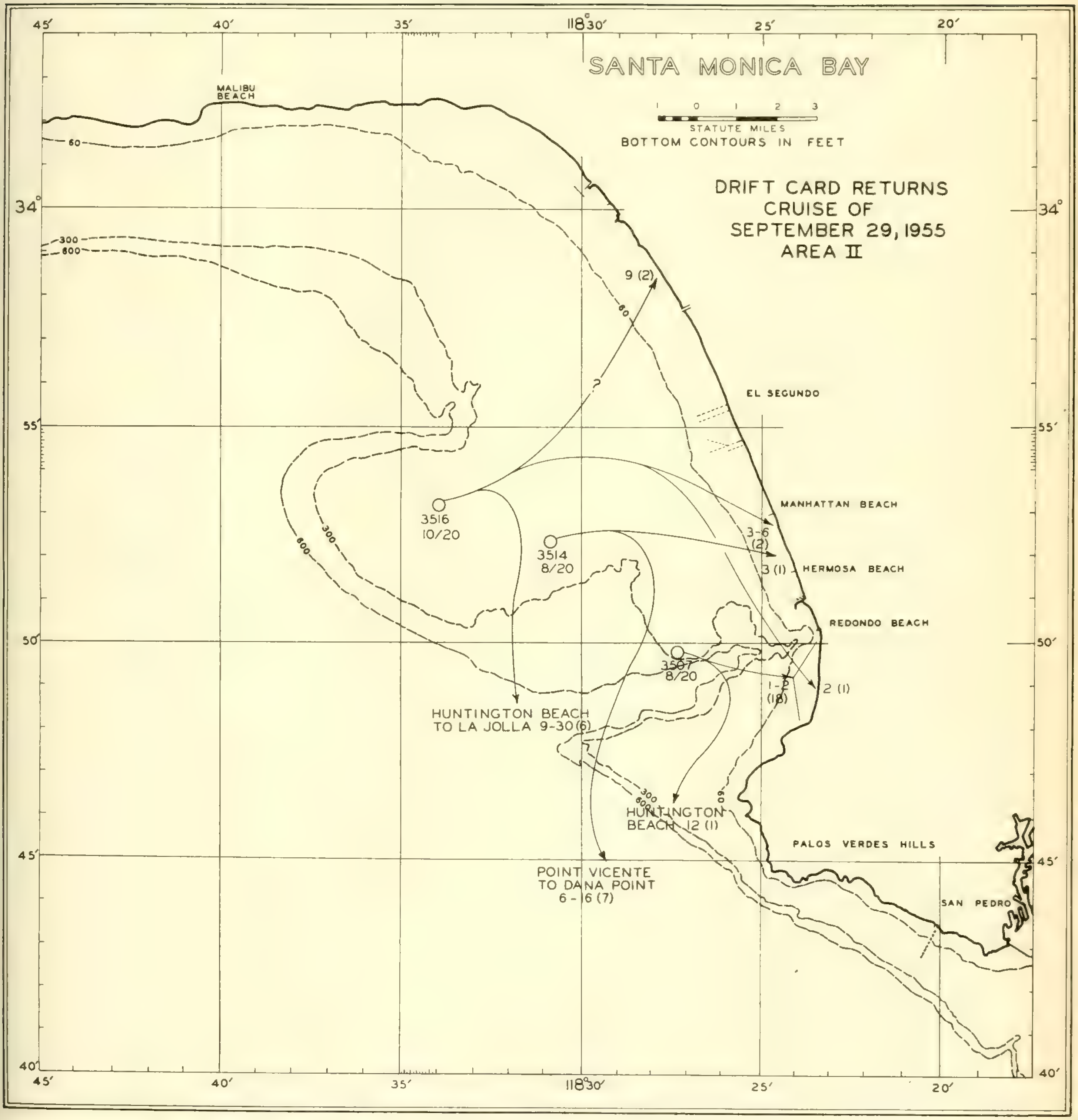
Returns from Area III are shown in Figure 89. This area lies inshore and includes the 5-mile stations in the northern half of the bay and all but one of the 3-mile stations. From all except the most northerly stations the cards came almost directly ashore with maximum velocities of about 5 miles per day (0.2 MPH). Returns from this area give the first indication of a divergence in the water as it flows toward shore. The divergence will be shown to be characteristic of Santa Monica Bay whenever a general flow from the west occurs. On

Figure 87. Drift card recoveries outside Santa Monica Bay, September 29, 1955, Areas I and II.



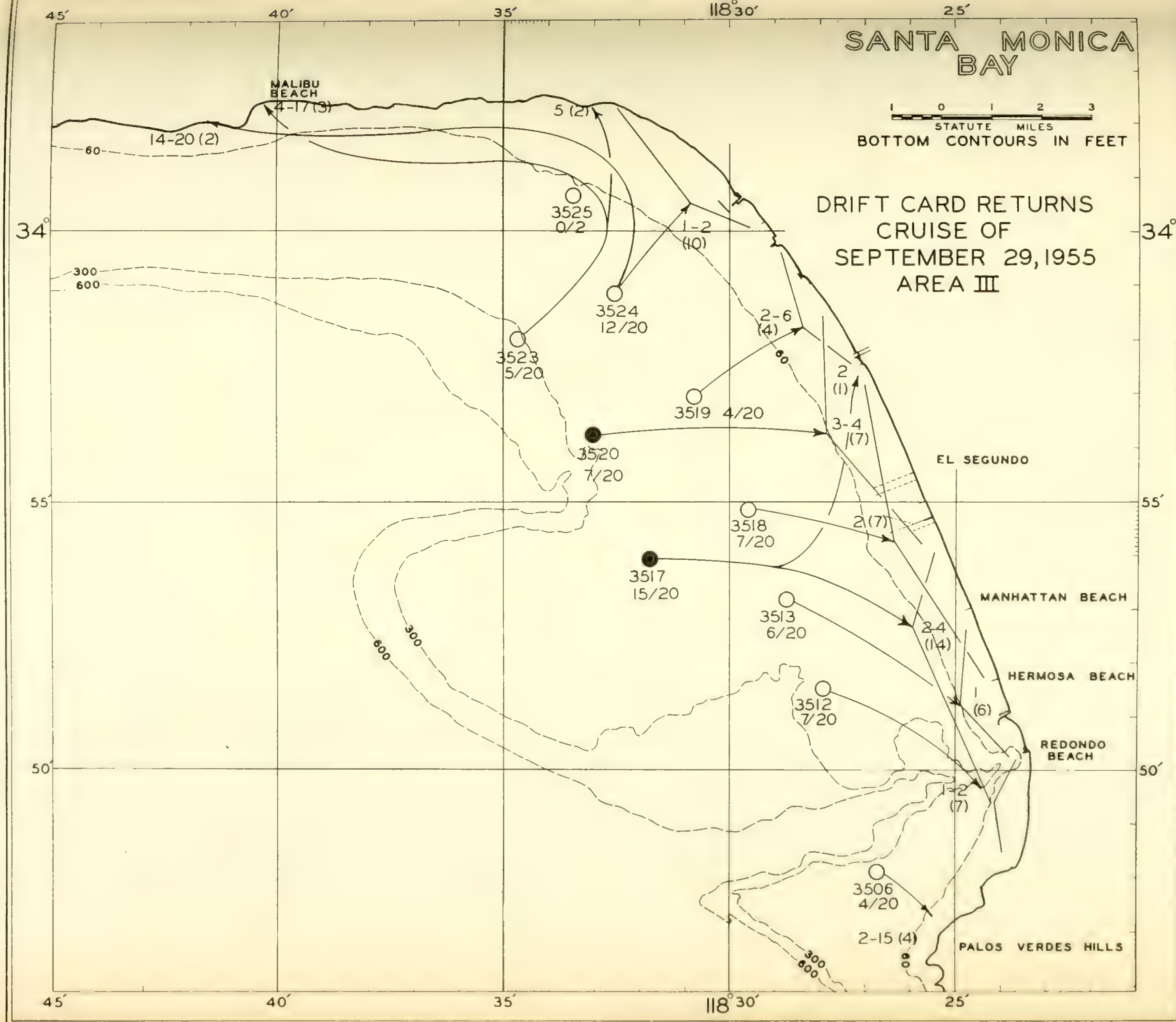
DRIFT CARD RETURNS
CRUISE OF
SEPTEMBER 29, 1955

Figure 88. Drift card recoveries, September 29, 1955, Area II.



SANTA MONICA BAY
STATUTE MILES
BOTTOM CONTOURS IN FEET
DRIFT CARD RETURNS
CRUISE OF
SEPTEMBER 29, 1955
AREA II
MALIBU BEACH
EL SEGUNDO
MANHATTAN BEACH
HERMOSA BEACH
REDONDO BEACH
PALOS VERDES HILLS
SAN PEDRO
9 (2)
3-6
(2)
3 (1)
2 (1)
1-2
(18)
3516
10/20
3514
8/20
3507
8/20
HUNTINGTON BEACH
TO LA JOLLA 9-30 (6)
HUNTINGTON
BEACH 12 (1)
POINT VICENTE
TO DANA POINT
6 - 16 (7)
118°30′
34°
55′
50′
45′
40′

Figure 89. Drift card recoveries, September 29, 1955
Area III.


SANTA MONICA BAY
STATUTE MILES
BOTTOM CONTOURS IN FEET
DRIFT CARD RETURNS
CRUISE OF
SEPTEMBER 29, 1955
AREA III
MALIBU BEACH
4-17 (3)
14-20 (2)
5 (2)
3525
0/2
1-2
(10)
3524
12/20
3523
5/20
2-6
(4)
2
(1)
3519 4/20
3-4
(7)
3520
7/20
EL SEGUNDO
3518
7/20
2 (7)
3517
15/20
MANHATTAN BEACH
3513
6/20
2-4
(14)
HERMOSA BEACH
1
(6)
3512
7/20
REDONDO BEACH
1-2
(7)
3506
4/20
2-15 (4)
PALOS VERDES HILLS
60
300
600
34°
55'
50'
45'
40'
35'
118° 30'
25'

this cruise not only do the lower stations show a southerly and the upper stations a northerly component superimposed upon a spreading of cards due to random dispersal, but returns from individual stations demonstrate beyond question the existence of such a divergence. After diverging, the water flows out and rounds the points of land at the northern and southern limits of the bay. The earlier anology between Santa Monica Bay and a bowl with water spilling over the edges is valid whenever the bay is being filled by an onshore drift. However, it will be shown by later cruises that the currents frequently flow either from the north or from the south and that during those times the bowl analogy does not apply.

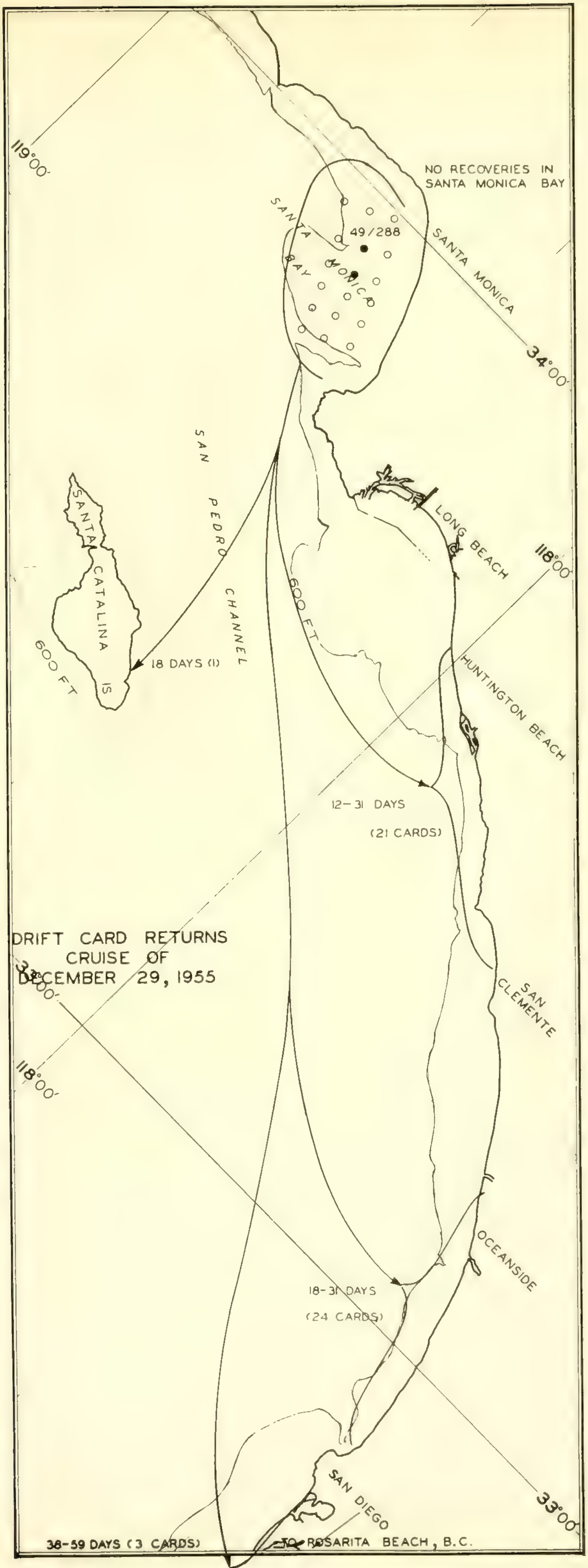
Cruise of December 29, 1955

The results of this cruise are presented on a single chart (Fig. 90), because of the 288 cards released in Santa Monica Bay and of the 49 (17%) that were recovered; all but two were returned from outside the bay and were scattered along the coast between Long Beach and Rosarito Beach, Baja California. One card was found floating in the water at Avalon Bay, Catalina Island. The maximum velocity determined was 4 miles per day (0.16 MPH).

Two cards were picked up by boatmen in Santa Monica Bay the day following release. Each had drifted about 3 miles from the stations of origin and were headed in such a direction (west of south) as to take them out of the bay had they continued in their drift.

During the day of release and during the following night and morning the sea was calm. There was no wind of any conse-

Figure 90. Drift card recoveries, December 29, 1955



DRIFT CARD RETURNS
CRUISE OF
DECEMBER 29, 1955
NO RECOVERIES IN
SANTA MONICA BAY
49/288
SANTA MONICA BAY
SANTA MONICA
34°00'
119°00'
SAN PEDRO CHANNEL
SANTA CATALINA IS
600 FT
18 DAYS (1)
LONG BEACH
118°00'
HUNTINGTON BEACH
12–31 DAYS
(21 CARDS)
33°00'
SAN CLEMENTE
OCEANSIDE
18-31 DAYS
(24 CARDS)
SAN DIEGO
38-59 DAYS (3 CARDS)
TO ROSARITA BEACH, B.C.

quence and only a barely perceptible swell was present. Between 9 a.m. and 1 p.m. on the day after releasing the cards, the VELERO IV recovered several of the cards and sighted at least three other groups of cards floating in the water. The ones recovered were from two different stations and had drifted only about one mile south from their points of release. All of these cards were returned to the water, but were not subsequently recovered.

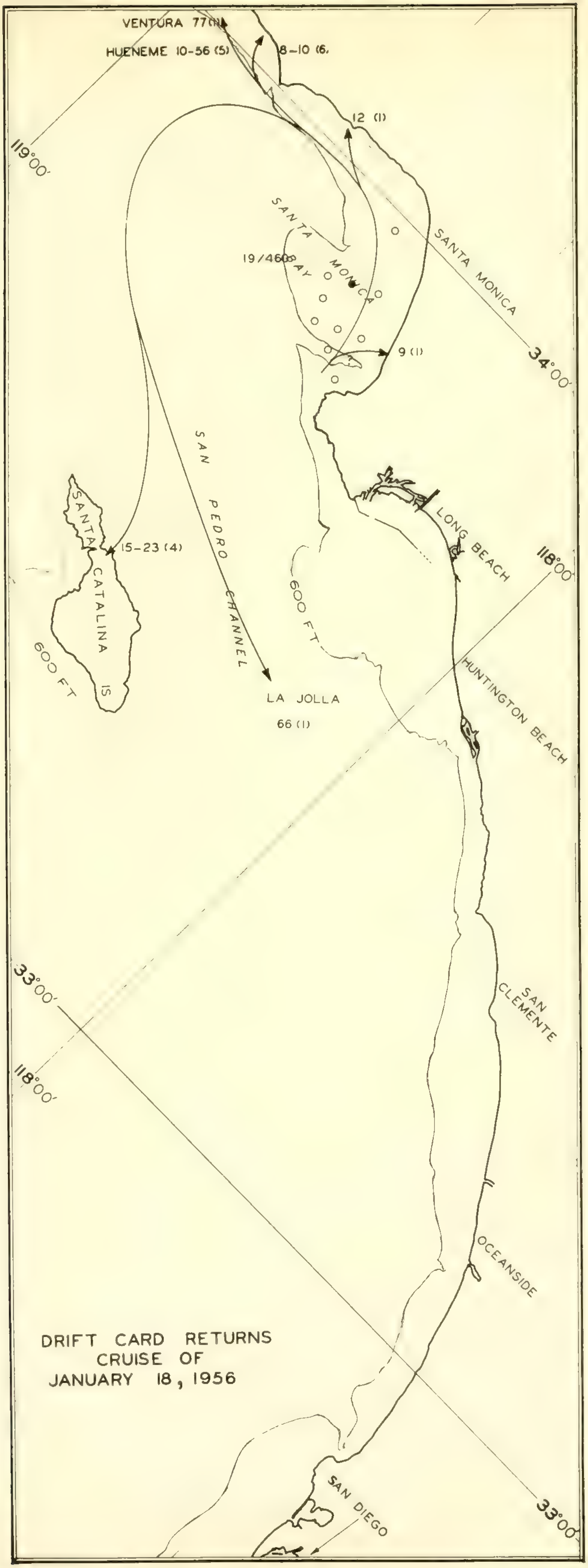
Under these conditions of extreme calm and weak currents, the cards were observed in clusters of four to ten or more whose radii were of the order of 50 to 200 yards even after nearly twenty four hours of drift.

Cruise of January 18, 1956

The current pattern in January was diametrically opposed to that on December 29 (Fig. 91). Drift within the bay was strongly to the north instead of to the south. In principal, the pattern was reminiscent of the one on September 8, when currents flowed to the north and then turned west past Malibu and Point Dume. However, the currents on January 18 were more strongly developed. On September 8, a great many cards were recovered in the bay. On January 18, only two cards were found on the same beaches, but twelve were returned from the coast between Point Dume and Ventura.

There were four returns from Catalina Island and one from La Jolla. This fact, together with the low percentage of returns (4% from all stations) clearly indicates that after escaping from Santa Monica Bay via its northern portal most of the cards were carried well out to sea and to the south.

Figure 91. Drift card returns, January 18, 1956



VENTURA 77(1)
HUENEME 10-56 (5)
8-10 (6)
12 (1)
119°00'
SANTA MONICA BAY
19/460
SANTA MONICA
9 (1)
34°00'
SAN PEDRO CHANNEL
SANTA CATALINA IS
15-23 (4)
600 FT
LONG BEACH
118°00'
HUNTINGTON BEACH
LA JOLLA
66 (1)
33°00'
SAN CLEMENTE
OCEANSIDE
SAN DIEGO
DRIFT CARD RETURNS
CRUISE OF
JANUARY 18, 1956

Maximum velocities were of the order of 3 miles per day (0.12 MPH). This figure probably is somewhat low as the coast north of Malibu is not frequented to any extent at this time of the year.

Cruise of February 16, 1956

This was an extra cruise not planned as part of the regular schedule (Fig. 92). Twenty cards were released at each of three stations, at the proposed terminals of the sludge and effluent outfalls, and one to the south, seven miles west of Redondo. Only one card was returned. It was released at the sludge outfall and picked up near Lunada Bay, Palos Verdes, sixteen days later. The travel time of this isolated card cannot be considered significant because the area is one of high cliffs and rocky shores, and recoveries even in the summer time are likely to be infrequent or delayed. Its direction of travel, together with the poor returns from all three stations, seems to indicate a dominant southerly flow from the portion of the bay in which the stations were located.

Cruise of February 22, 1956

As on certain other cruises, the bay was divided into two areas determined by significant differences in direction of flow (Fig. 93).

From the southern portion of the bay (Area I, Fig. 94), a few recoveries were made at Malaga Cove. However, one card rounded the Palos Verdes Hills and was recovered at Torrey Pines, eighty miles to the south. No cards were recovered from three stations of the seven, and the percentage of

Figure 92. Drift card returns, February 16, 1956

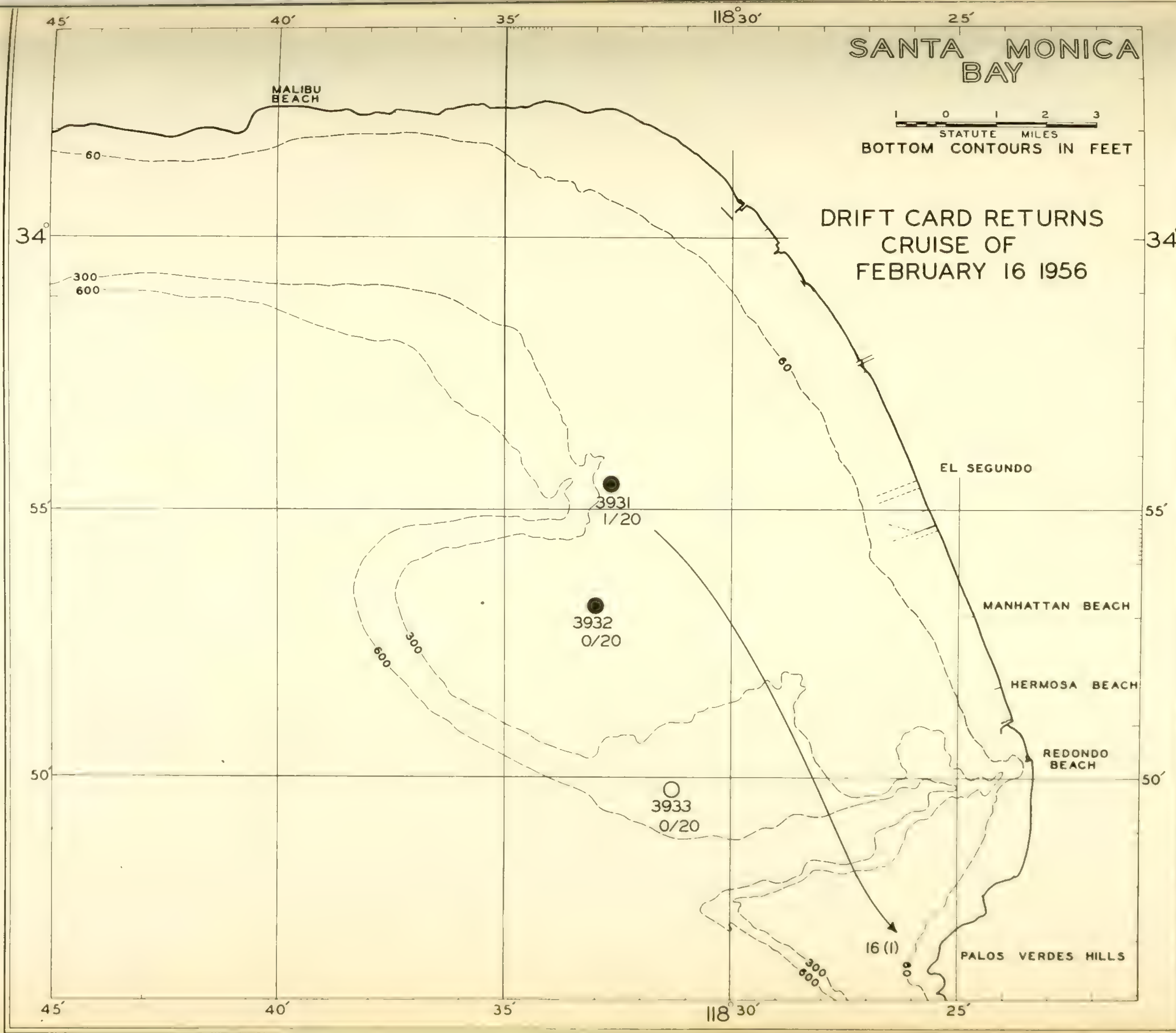

SANTA MONICA BAY
STATUTE MILES
BOTTOM CONTOURS IN FEET
DRIFT CARD RETURNS
CRUISE OF
FEBRUARY 16 1956
MALIBU BEACH
EL SEGUNDO
MANHATTAN BEACH
HERMOSA BEACH
REDONDO BEACH
PALOS VERDES HILLS
3931
1/20
3932
0/20
3933
0/20
16 (1)
118°30′
34°

Figure 93. Drift card stations, February 22, 1956

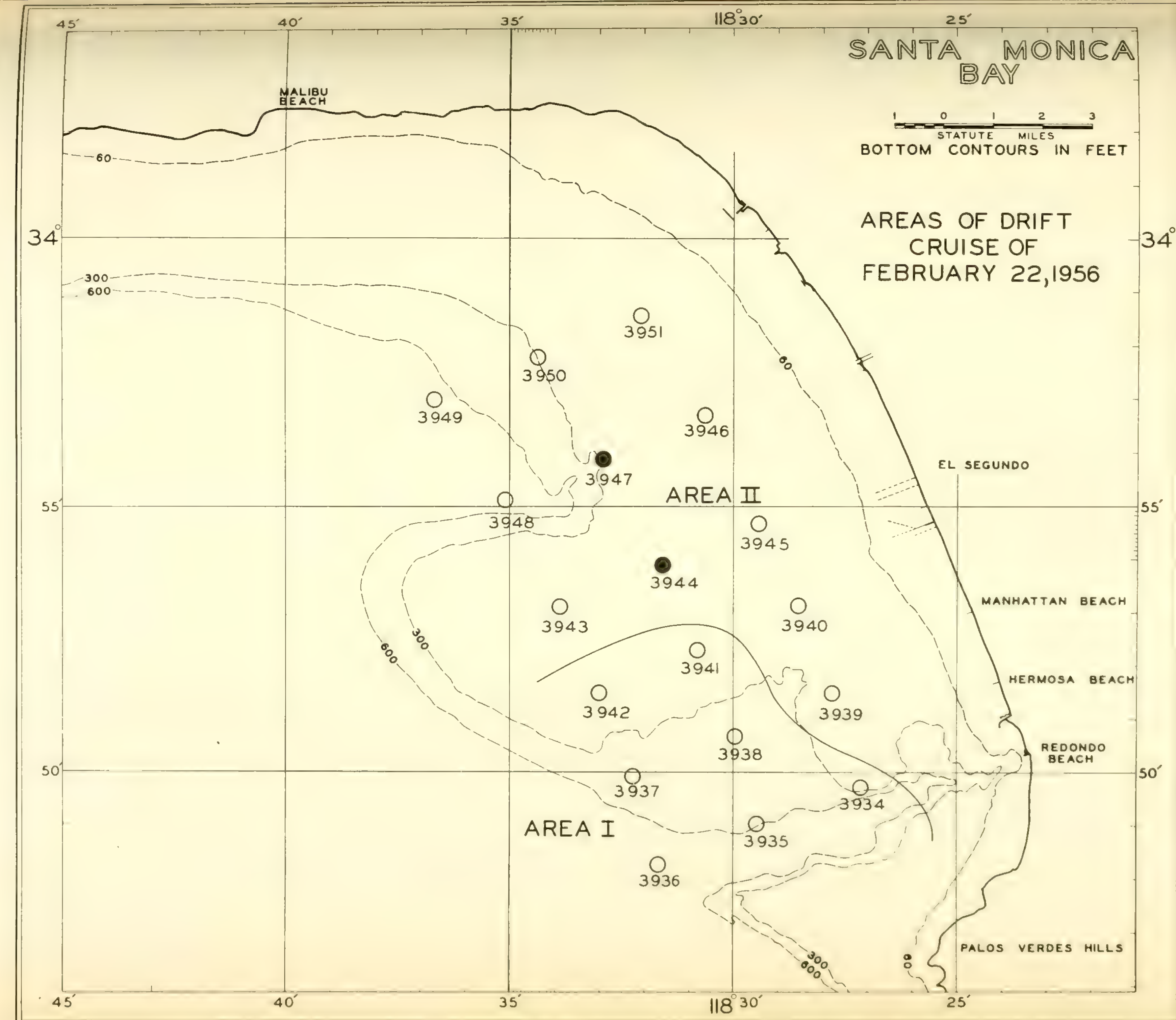
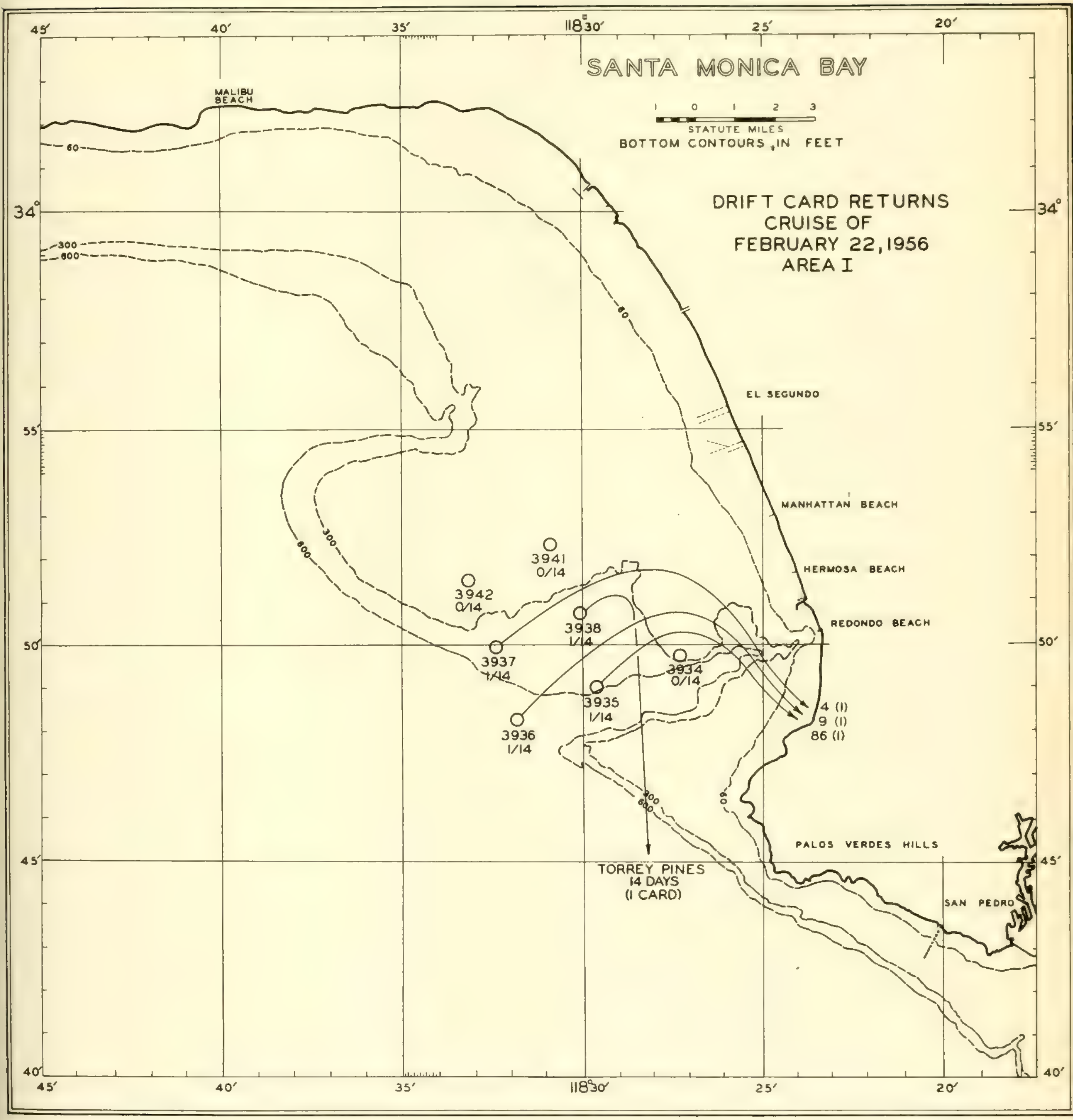

SANTA MONICA BAY
1 0 1 2 3
STATUTE MILES
BOTTOM CONTOURS IN FEET
AREAS OF DRIFT
CRUISE OF
FEBRUARY 22, 1956
MALIBU BEACH
EL SEGUNDO
MANHATTAN BEACH
HERMOSA BEACH
REDONDO BEACH
PALOS VERDES HILLS
AREA II
AREA I
3934
3935
3936
3937
3938
3939
3940
3941
3942
3943
3944
3945
3946
3947
3948
3949
3950
3951
60
300
600
45'
40'
35'
118°30'
25'
34°
55'
50'

Figure 94. Drift card returns, February 22, 1956
Area I.



SANTA MONICA BAY
STATUTE MILES
BOTTOM CONTOURS, IN FEET
DRIFT CARD RETURNS
CRUISE OF
FEBRUARY 22, 1956
AREA I
MALIBU BEACH
EL SEGUNDO
MANHATTAN BEACH
HERMOSA BEACH
REDONDO BEACH
PALOS VERDES HILLS
SAN PEDRO
3941 0/14
3942 0/14
3938 1/14
3937 1/14
3934 0/14
3935 1/14
3936 1/14
4 (1)
9 (1)
86 (1)
TORREY PINES
14 DAYS
(1 CARD)

returns from the other four was extremely low (only 1 card of 14 released at each station, or 7%). These facts combine to indicate that a well-defined southerly current was present which flowed past the Palos Verdes Hills and carried most of the cards south and to sea. The one 86-day recovery from Station 3435 is of no special significance. The adjacent coast is rocky and precipitous, is seldom visited in February, and a card easily may be hidden or overlooked for a considerable period of time.

Within Area II (Fig. 95) the general trend was toward the shore and there is a clear indication of an inshore divergence similar to that noted previously on September 29. Because of the relatively long travel time of 6 days from Stations 3949 and 3950 on the northernmost line of stations, a small gyral may have been present in the northern portion of the bay.

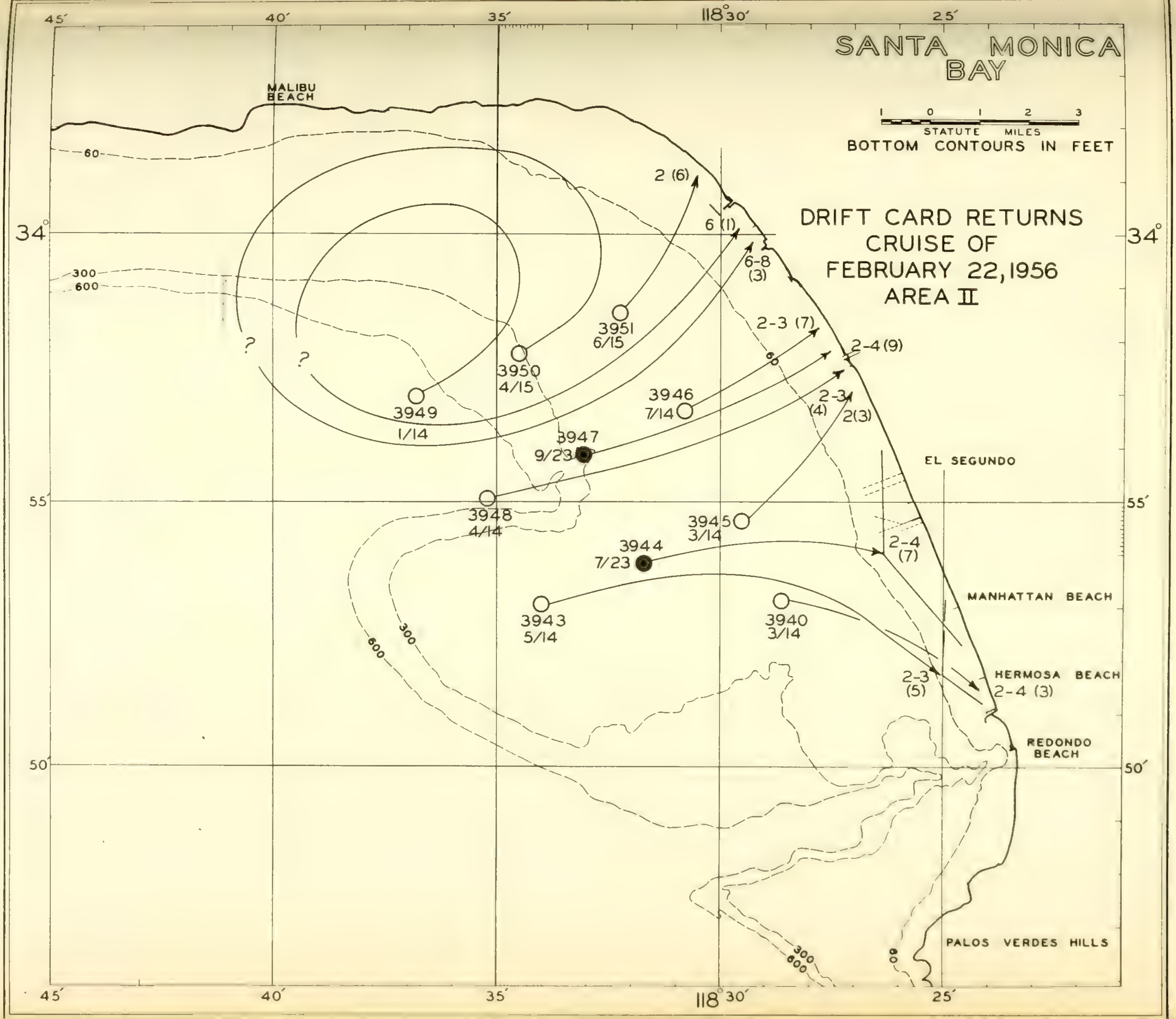
Cards returned were only 55 out of 272 released (20%), although the recoveries were better from the northern than from the southern stations. Maximum velocities were 4 3/4 miles per day (0.20 MPH).

Cruise of March 28, 1956

On this cruise the customary stations were occupied but with one additional group of cards being released at the southernmost entrance to the bay, about one mile west of Flat Rock Point.

A large number of recoveries were made, 243 out of 550 cards (44%) being returned. Because of the large recovery and of the relatively simple current pattern, a slightly

Figure 95. Drift card returns, February 22, 1956
Area II.


SANTA MONICA BAY
STATUTE MILES
BOTTOM CONTOURS IN FEET
DRIFT CARD RETURNS
CRUISE OF
FEBRUARY 22,1956
AREA II
MALIBU BEACH
EL SEGUNDO
MANHATTAN BEACH
HERMOSA BEACH
REDONDO BEACH
PALOS VERDES HILLS
3949
1/14
3950
4/15
3951
6/15
3946
7/14
3947
9/23
3948
4/14
3945
3/14
3944
7/23
3943
5/14
3940
3/14
2 (6)
6 (1)
6-8
(3)
2-3 (7)
2-4 (9)
2-3
(4)
2(3)
2-4
(7)
2-3
(5)
2-4 (3)
118°30′

different method of presentation of results is used for this cruise. In Figures 96, 97, and 98, returns for groups of stations are plotted and the general areas of recovery from each group indicated by brackets. The dashed lines on these charts and those for succeeding cruises separate areas of different times of drift.

Several salient facts are evident. From all stations including the one off Flat Rock Point the general drift was to the north and inshore. Cards were recovered between Topanga Canyon on the north and Malaga Cove on the south. Only one card was returned from Malibu and none from outside the bay. Although the general trend was to the north, some evidence of an inshore divergence can be seen. Because the divergence was not as prominent as on other occasions, the spread of cards in this case might be interpreted as due to a littoral dirft which carried them farther to the south than would have been expected on the basis of random physical diffusion alone.

The maximum velocity encountered on this cruise was 5 miles per day (0.21 MPH), but most values were considerably less.

Cruise of April 25, 1956

The general pattern of circulation within the bay was similar to that on the preceeding cruise, inshore and to the north from all stations. Here also returns from many stations can be grouped together and their graphic representation simplified.

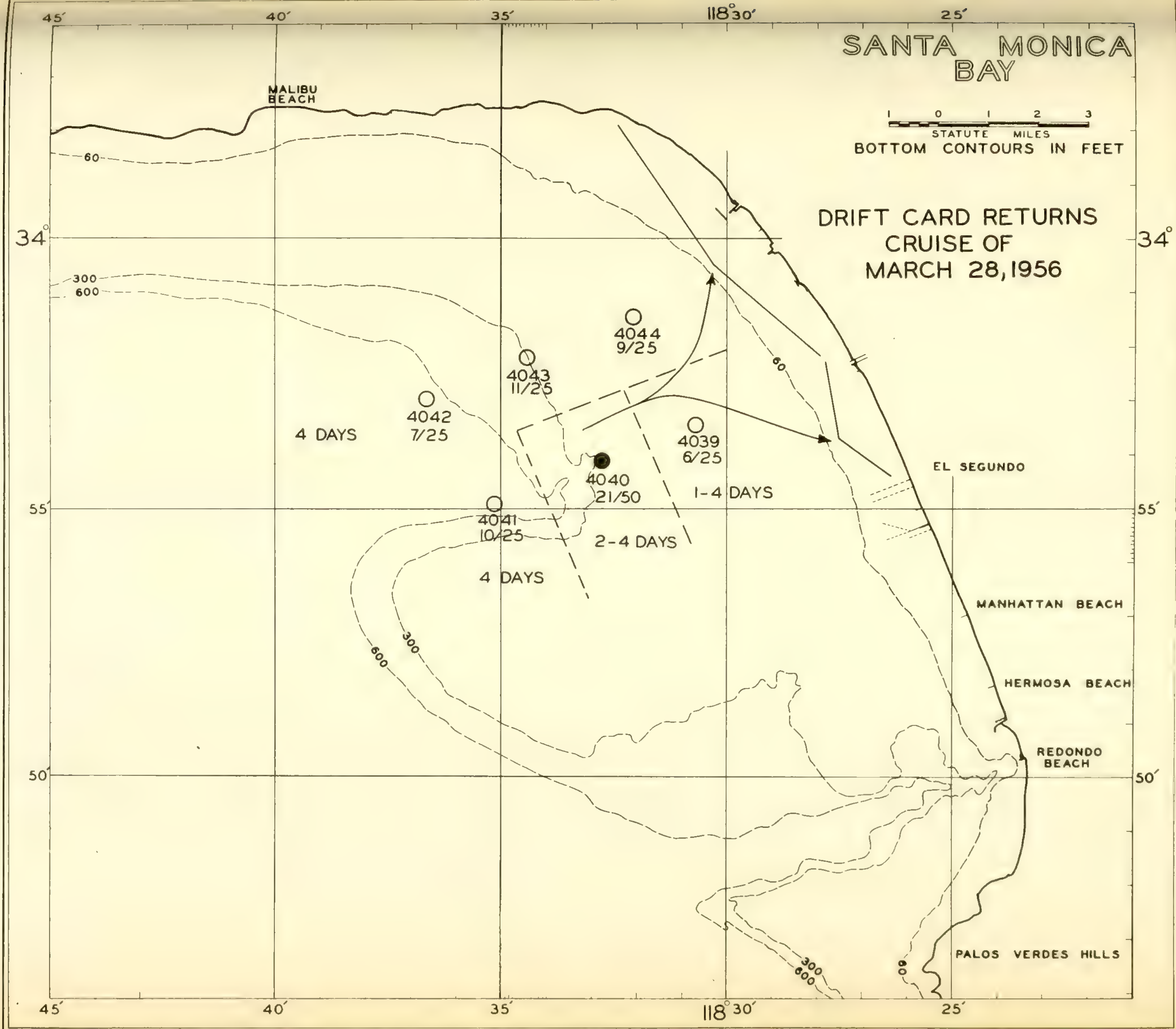
Figure 96. Drift card returns, March 28, 1956

SANTA MONICA BAY
STATUTE MILES
BOTTOM CONTOURS IN FEET
DRIFT CARD RETURNS
CRUISE OF
MARCH 28 1956
MALIBU BEACH
EL SEGUNDO
MANHATTAN BEACH
HERMOSA BEACH
REDONDO BEACH
PALOS VERDES HILLS
2 DAYS
2-4 DAYS
4 DAYS
1-4 DAYS
4025 14/25
4026 7/25
4027 14/25
4028 15/25
4029 12/25
4030 12/25
4031 10/25
4032 10/25
118°30′
34°

Figure 97. Drift card returns, March 28, 1956


SANTA MONICA BAY
STATUTE MILES
BOTTOM CONTOURS IN FEET
DRIFT CARD RETURNS
CRUISE OF
MARCH 28, 1956
MALIBU BEACH
EL SEGUNDO
MANHATTAN BEACH
HERMOSA BEACH
REDONDO BEACH
PALOS VERDES HILLS
2-4 DAYS
2-5 DAYS
3-5 DAYS
4038 9/25
4037 28/50
4036 18/25
4035 15/25
4034 8/25
4033 7/25
3 (1)
118°30′
34°
55′
50′
45′
40′
35′
25′

Figure 98. Drift card returns, March 28, 1956


SANTA MONICA BAY
1 0 1 2 3
STATUTE MILES
BOTTOM CONTOURS IN FEET
DRIFT CARD RETURNS
CRUISE OF
MARCH 28, 1956
MALIBU BEACH
EL SEGUNDO
MANHATTAN BEACH
HERMOSA BEACH
REDONDO BEACH
PALOS VERDES HILLS
4044
9/25
4043
11/25
4042
7/25
4039
6/25
4040
21/50
4041
10/25
4 DAYS
1-4 DAYS
2-4 DAYS
4 DAYS
60
300
600
34°
55′
50′
45′
40′
35′
118°30′
25′

Cards from the southern half of the bay (Fig. 99) were scattered mostly between Santa Monica and Manhattan Beach, with only six from Redondo and Torrance Beach. All the latter cards originated from the southernmost Station, No. 4197.

From the northern half of the bay (Fig. 100), recoveries were predominantly from Malibu to El Segundo. A number of cards were recovered from the Manhattan-Redondo region, but all of these came from the same Station, No. 4208.

In general, the trend of the currents seemed to be inshore, with a moderate northern component, but on this cruise there was little evidence of any well-developed inshore divergence in currents. The spread of cards from each of the various stations could be explained on the basis of shoreward movement and random dispersal.

Because of the predominant inshore drift from all stations, 53% of the cards released during the cruise were returned (276 out of 520).

The maximum velocity on this cruise was obtained from Station 4203 in the southern part of the bay. From here one card was picked up at Santa Monica 29 hours after its release and on the afternoon of the following day, at a point about 15 miles distant (0.52 MPH). From all other stations, the maximum recorded velocities were less, but in some cases were appreciably greater than on previous cruises. For this reason all of the most rapid drifts on this cruise are summarized in Table X.

Figure 99. Drift card returns, April 25, 1956

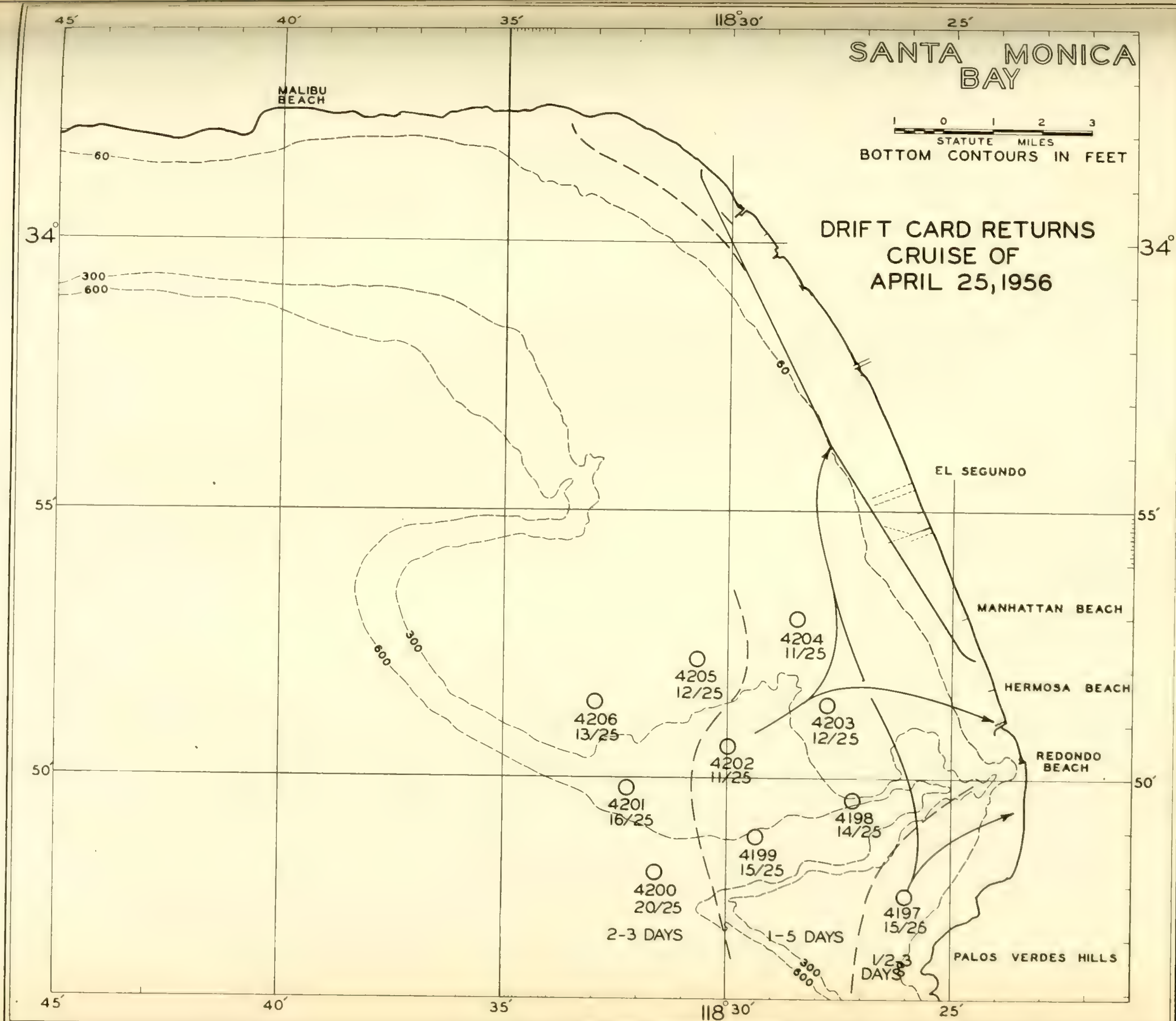

SANTA MONICA BAY
1 0 1 2 3
STATUTE MILES
BOTTOM CONTOURS IN FEET
DRIFT CARD RETURNS
CRUISE OF
APRIL 25, 1956
MALIBU BEACH
EL SEGUNDO
MANHATTAN BEACH
HERMOSA BEACH
REDONDO BEACH
PALOS VERDES HILLS
60
300
600
4204
11/25
4205
12/25
4206
13/25
4203
12/25
4202
11/25
4201
16/25
4198
14/25
4199
15/25
4200
20/25
4197
15/25
2-3 DAYS
1-5 DAYS
1/2-3
DAYS
45′
40′
35′
118°30′
25′
34°
55′
50′

Figure 100. Drift card returns, April 25, 1956

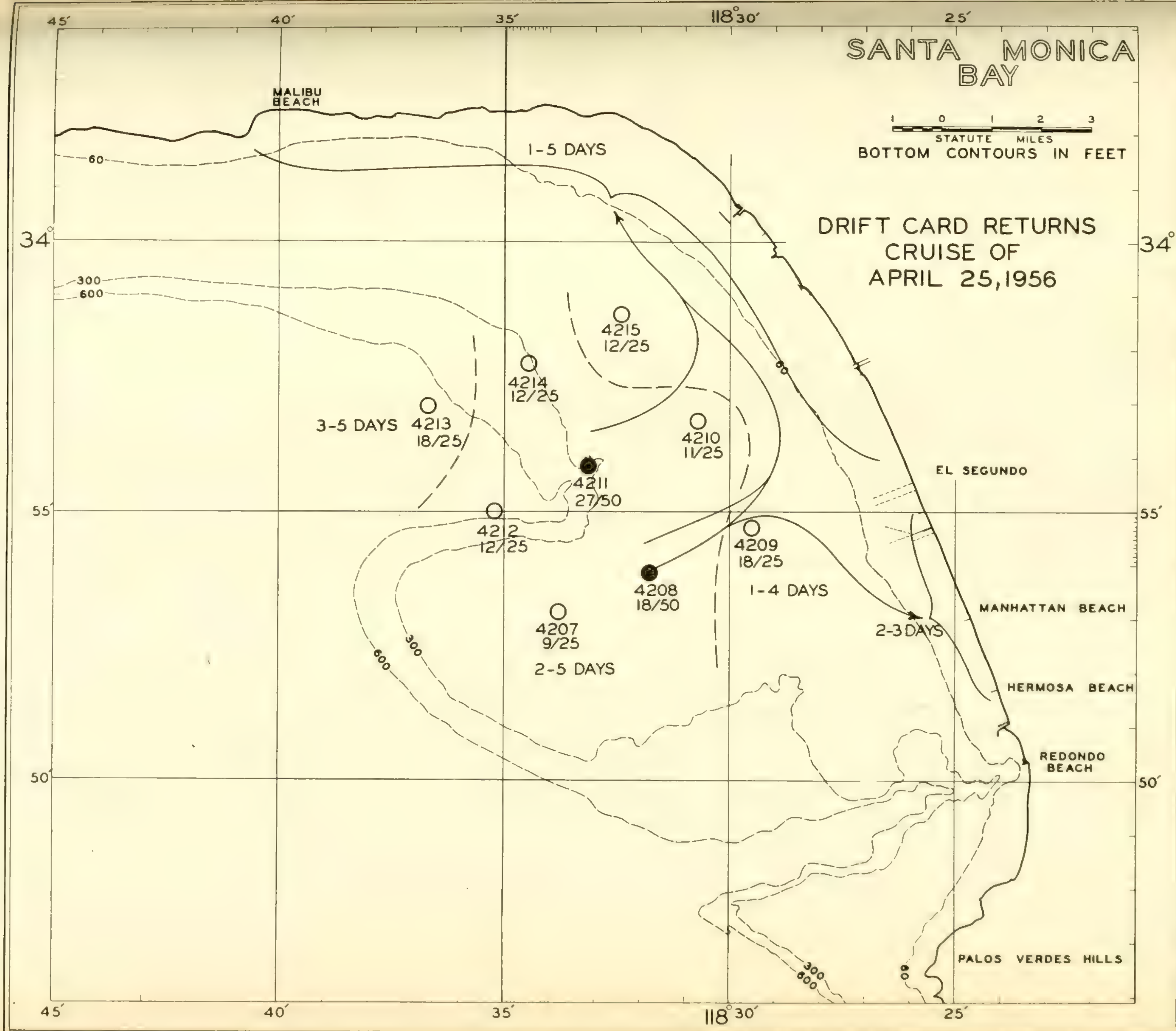

SANTA MONICA BAY
STATUTE MILES
1 0 1 2 3
BOTTOM CONTOURS IN FEET
DRIFT CARD RETURNS
CRUISE OF
APRIL 25,1956
MALIBU BEACH
EL SEGUNDO
MANHATTAN BEACH
HERMOSA BEACH
REDONDO BEACH
PALOS VERDES HILLS
1-5 DAYS
3-5 DAYS
2-5 DAYS
1-4 DAYS
2-3 DAYS
4215 12/25
4214 12/25
4213 18/25
4210 11/25
4211 27/50
4212 12/25
4209 18/25
4208 18/50
4207 9/25
60
300
600
45′
40′
35′
118°30′
25′
34°
55′
50′

TABLE X

MAXIMUM VELOCITIES OF DRIFT CARDS

April 25, 1956

Station	Point of Recovery	Distance Travelled	Time of Travel	Velocity Miles/day	Velocity MPH
4197	Redondo to Torrance (4 cards)	2.5-4 mi.	8-9 hr.	12	0.50
4199	South Playa del Rey (1)	8	$20\frac{1}{2}$	$9\frac{1}{2}$	0.39
4202	Santa Monica (1 card)	11	$17\frac{1}{2}$	11	0.45
4203	Santa Monica (5 cards)	10	28	$8\frac{1}{2}$	0.36
		15	29	$12\frac{1}{2}$	0.52
		$9\frac{1}{2}$	$25\frac{1}{2}$	9	0.37
		10	$27\frac{1}{2}$	$8\frac{1}{2}$	0.36
		13	30	$10\frac{1}{2}$	0.43
4204	Will Rogers Beach (1)	9	27	8	0.33
	Sunset Blvd. (2 cards)	10	27-29	$8\frac{1}{2}$-9	0.37

It is to be noted that these relatively high velocities are all from stations in the southern and more inshore portions of the bay. No such velocities were recorded from any other station; most of the cards drifting at a rate of 5 miles per day (0.21 MPH or less).

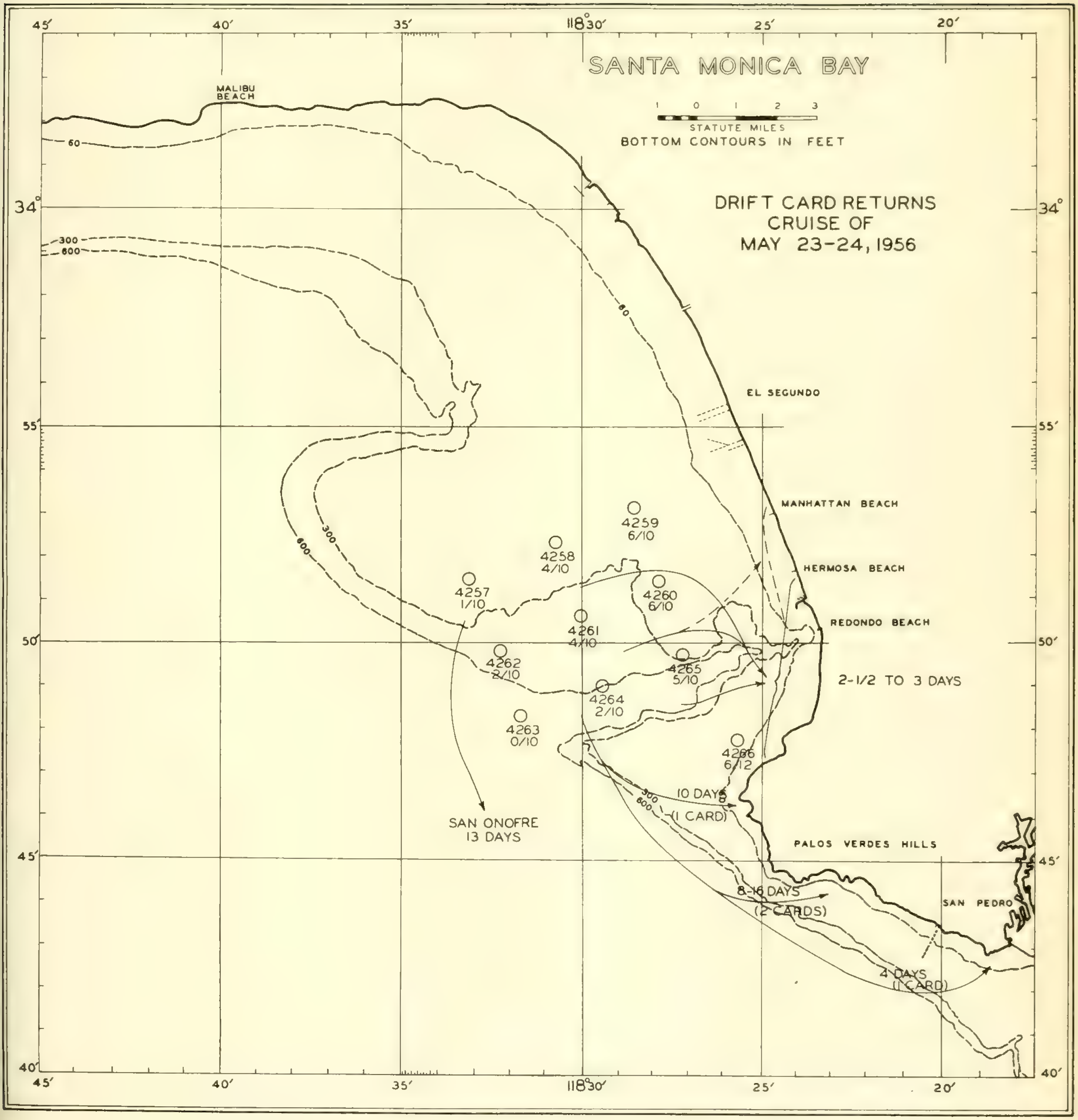
Cruise of May 23-24, 1956

On May 22, 1956, an experiment at the Hyperion outfall was conducted using a radioactive tracer in the effluent. Between 10 p.m. and 3 a.m. on the night of May 23-24, drift cards were released over the usual series of stations in Santa Monica Bay. In Figures 101 and 102 are the results of these releases.

Thirty eight per cent of all cards were recovered (95 out of 252). They demonstrate a modification in direction of flow from the April 25 cruise. The predominant direction was still inshore, but there was a moderate to strong southerly component from most stations instead of a moderate northerly one as on the previous cruise. With few exceptions, cards from all but the northern two station lines went inshore and south. A few rounded Point Vicente and were recovered from Lunada Bay, Portuguese Bend, and San Pedro. From Station 4257 the one card returned was from San Onofre. There were no recoveries from Station 4263, as these cards probably went south through San Pedro Channel and were lost. Another point of evidence for a strong southerly flow from the lower half of the bay is found in the fact that along the three southernmost lines the percentage of recoveries decreased with increasing distance from shore, from 50% to 10%.

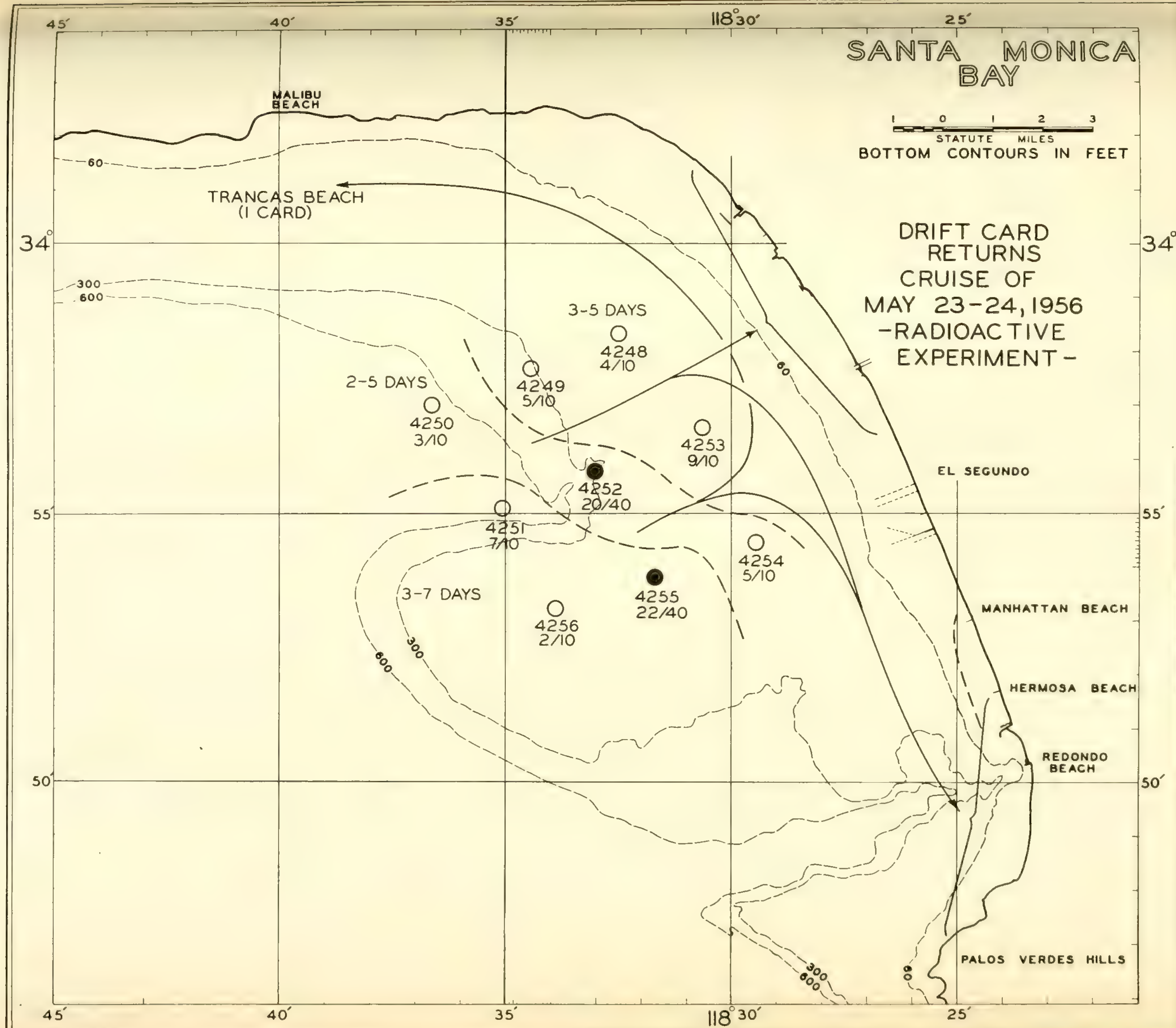
From the northern lines of stations (4248, 4249, and 4250), the cards were carried more directly inshore to the area between Santa Monica and Playa del Rey, but from the line just below (4251, 4252, and 4253) a definite southerly drift was apparent.

Figure 101. Drift card returns, May 23-24, 1956



SANTA MONICA BAY
STATUTE MILES
BOTTOM CONTOURS IN FEET
DRIFT CARD RETURNS
CRUISE OF
MAY 23-24, 1956
MALIBU BEACH
EL SEGUNDO
MANHATTAN BEACH
HERMOSA BEACH
REDONDO BEACH
PALOS VERDES HILLS
SAN PEDRO
2-1/2 TO 3 DAYS
10 DAYS
(1 CARD)
8-16 DAYS
(2 CARDS)
4 DAYS
(1 CARD)
SAN ONOFRE
13 DAYS
4257 1/10
4258 4/10
4259 6/10
4260 6/10
4261 4/10
4262 2/10
4263 0/10
4264 2/10
4265 5/10
4266 6/12

Figure 102. Drift card returns, May 23-24, 1956


SANTA MONICA BAY
1 0 1 2 3
STATUTE MILES
BOTTOM CONTOURS IN FEET
DRIFT CARD RETURNS
CRUISE OF
MAY 23-24, 1956
-RADIOACTIVE EXPERIMENT-
MALIBU BEACH
TRANCAS BEACH (1 CARD)
EL SEGUNDO
MANHATTAN BEACH
HERMOSA BEACH
REDONDO BEACH
PALOS VERDES HILLS
3-5 DAYS
2-5 DAYS
3-7 DAYS
4248 4/10
4249 5/10
4250 3/10
4251 7/10
4252 20/40
4253 9/10
4254 5/10
4255 22/40
4256 2/10
60
300
600
45′
40′
35′
118°30′
25′
34°
55′
50′

The only indication of a northward littoral drift was given by a single recovery from the effluent outfall station (4255). From here one card was found at Trancas Beach north of Point Dume 18 days after release. All others from this station made their way to shore between Hermosa Beach and Flat Rock Point within 2½ to 4 days. Because of the long delay in recovery of the single card, its path was uncertain and likely it represented a change in current pattern occurring some time after the cruise of May 23-24.

The maximum velocity to the shore within the bay was lower than on the previous cruise, about 5.2 miles per day (0.22 MPH).

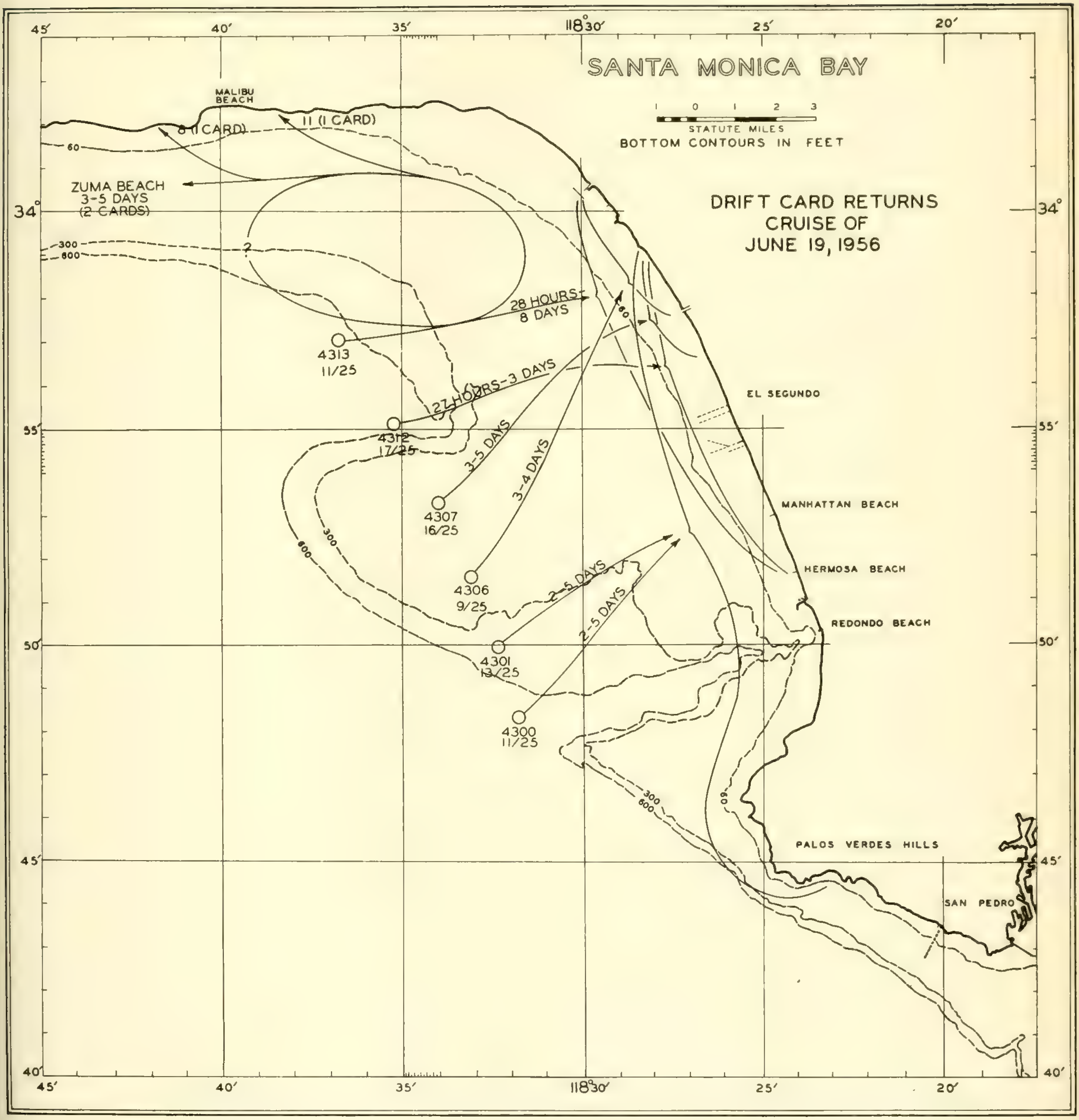
Cruise of June 19, 1956

On this date 525 cards were dropped in the usual pattern and of these 279 (53%) were returned. This was to have been the last scheduled drift card drop under the contract.

From the 7 and 5 mile stations (Figs. 103 and 104), cards drifted toward the shore with perhaps a suggestion of a slight northerly component. However, those returns, together with the ones from the 3 mile stations (Fig. 105), give strong evidence of both a divergence in the central inshore portion of the bay and a split into two branches, one running north and the other south. Returns from Station 4313 (Fig. 103) suggest either a large counter-clockwise gyral in the northern portion of the bay, or a drift to sea west past Point Dume and a subsequent delayed return into the bay.

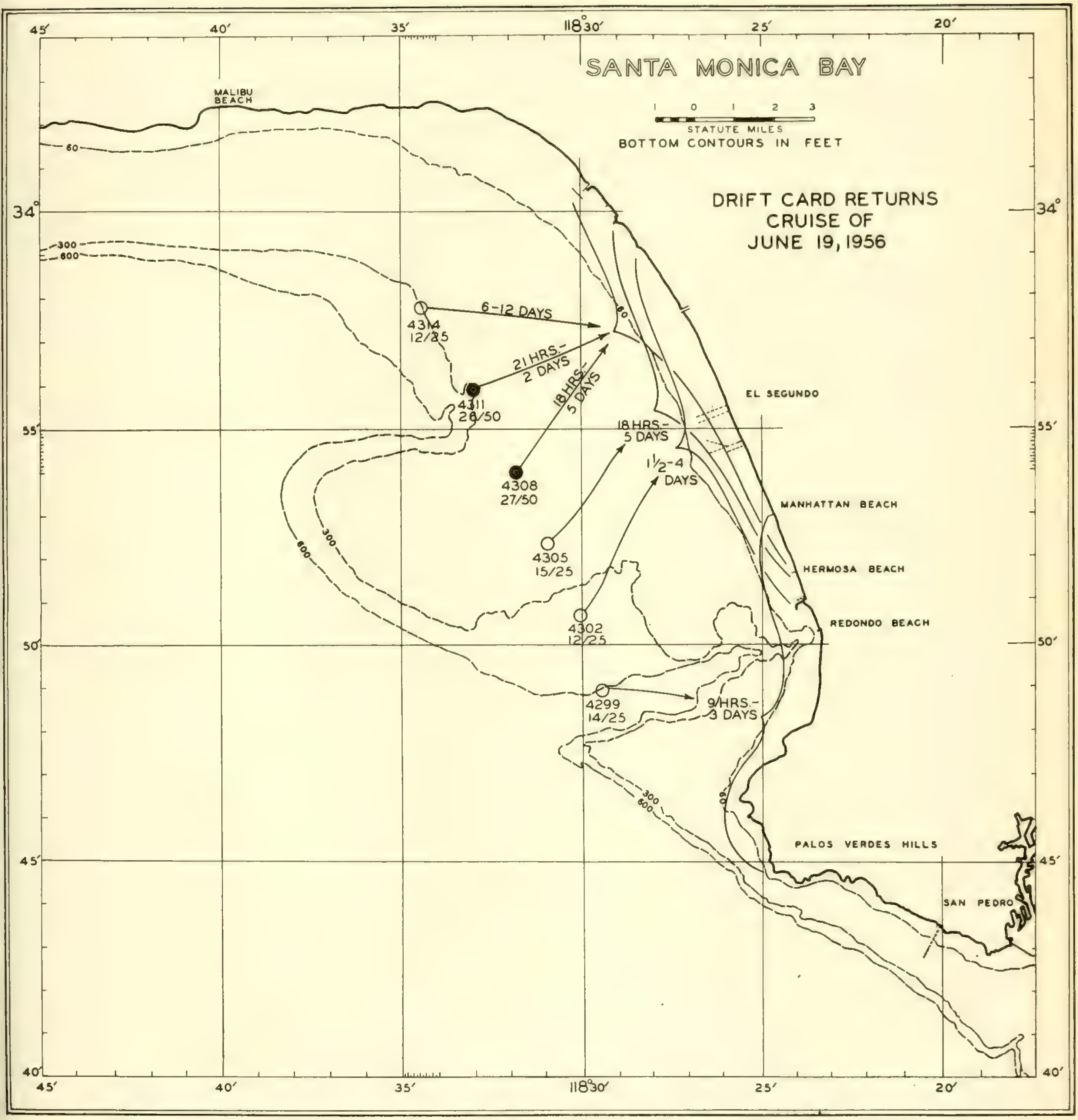
Moderate to high velocities were encountered on this cruise from several stations, including those located at the

Figure 103. Drift card returns, June 19, 1956



SANTA MONICA BAY
STATUTE MILES
BOTTOM CONTOURS IN FEET
DRIFT CARD RETURNS
CRUISE OF
JUNE 19, 1956
MALIBU BEACH
8 (1 CARD)
11 (1 CARD)
ZUMA BEACH
3-5 DAYS
(2 CARDS)
28 HOURS-
8 DAYS
4313
11/25
27 HOURS-3 DAYS
4312
17/25
3-5 DAYS
3-4 DAYS
4307
16/25
4306
9/25
2-5 DAYS
2-5 DAYS
4301
13/25
4300
11/25
EL SEGUNDO
MANHATTAN BEACH
HERMOSA BEACH
REDONDO BEACH
PALOS VERDES HILLS
SAN PEDRO
45′
40′
35′
118°30′
25′
20′
34°
55′
50′
45′
40′
60
300
600

Figure 104. Drift card returns, June 19, 1956



SANTA MONICA BAY
STATUTE MILES
BOTTOM CONTOURS IN FEET
DRIFT CARD RETURNS
CRUISE OF
JUNE 19, 1956
MALIBU BEACH
EL SEGUNDO
MANHATTAN BEACH
HERMOSA BEACH
REDONDO BEACH
PALOS VERDES HILLS
SAN PEDRO
6-12 DAYS
21 HRS.- 2 DAYS
18 HRS.- 5 DAYS
18 HRS.- 5 DAYS
1½-4 DAYS
9 HRS.- 3 DAYS
4314 12/25
4311 26/50
4308 27/50
4305 15/25
4302 12/25
4299 14/25
118°30′
34°
55′
50′
45′
40′

Figure 105. Drift card returns, June 19, 1956

SANTA MONICA BAY
STATUTE MILES
1 0 1 2 3
BOTTOM CONTOURS IN FEET
DRIFT CARD RETURNS
CRUISE OF
JUNE 19, 1956
MALIBU BEACH
2-3 (2 CARDS)
ZUMA BEACH
19 DAYS (1 CARD)
1-3
4315
11/25
1-3
4310
16/25
EL SEGUNDO
1-3
4309
17/25
MANHATTAN BEACH
4304
12/25
1-2
18 HRS.
3 DAYS
HERMOSA BEACH
4303
13/25
REDONDO BEACH
4298
15/25
7 1/2-11 HRS.
4297
11/25
2 1/2 HRS.-11 DAYS
PALOS VERDES HILLS
60
300
600
45′
40′
35′
118°30′
25′
34°
55′
50′

proposed sludge and effluent outfall terminals. All high velocity returns from these stations are summarized in Table XI.

Cruise of June 29, 1956

In connection with a salinity survey of the inshore area, drift cards were released on June 29 at each of ten stations along a line three miles from shore between Playa del Rey and Manhattan Beach. Station locations and results are presented in Figure 106. Sixty per cent of the cards were returned.

With few exceptions the cards drifted north and inshore, coming to the beach in the area between Santa Monica and Playa del Rey. The drift of only one card, from Station 4458, ended at a point south of its place of release.

Seven returns are of special interest because they were recovered on the same day, between 7 and 9 hours after release. All other cards were recovered the following morning, on June 30 or later. The velocities of these seven cards ranged between 0.38 and 0.54 MPH, or between 9.1 and 13.0 miles per day. The significance of these high velocities, as well as those found on the previous cruise of April 25, is discussed elsewhere.

Cruise of July 26-27, 1956

This was the first of three additional cruises made for the purpose of extending the drift card data through the summer months. On this cruise, as well as on the two following, cards were released during the night hours in order to make possible recoveries during the critical 8-20 hour period

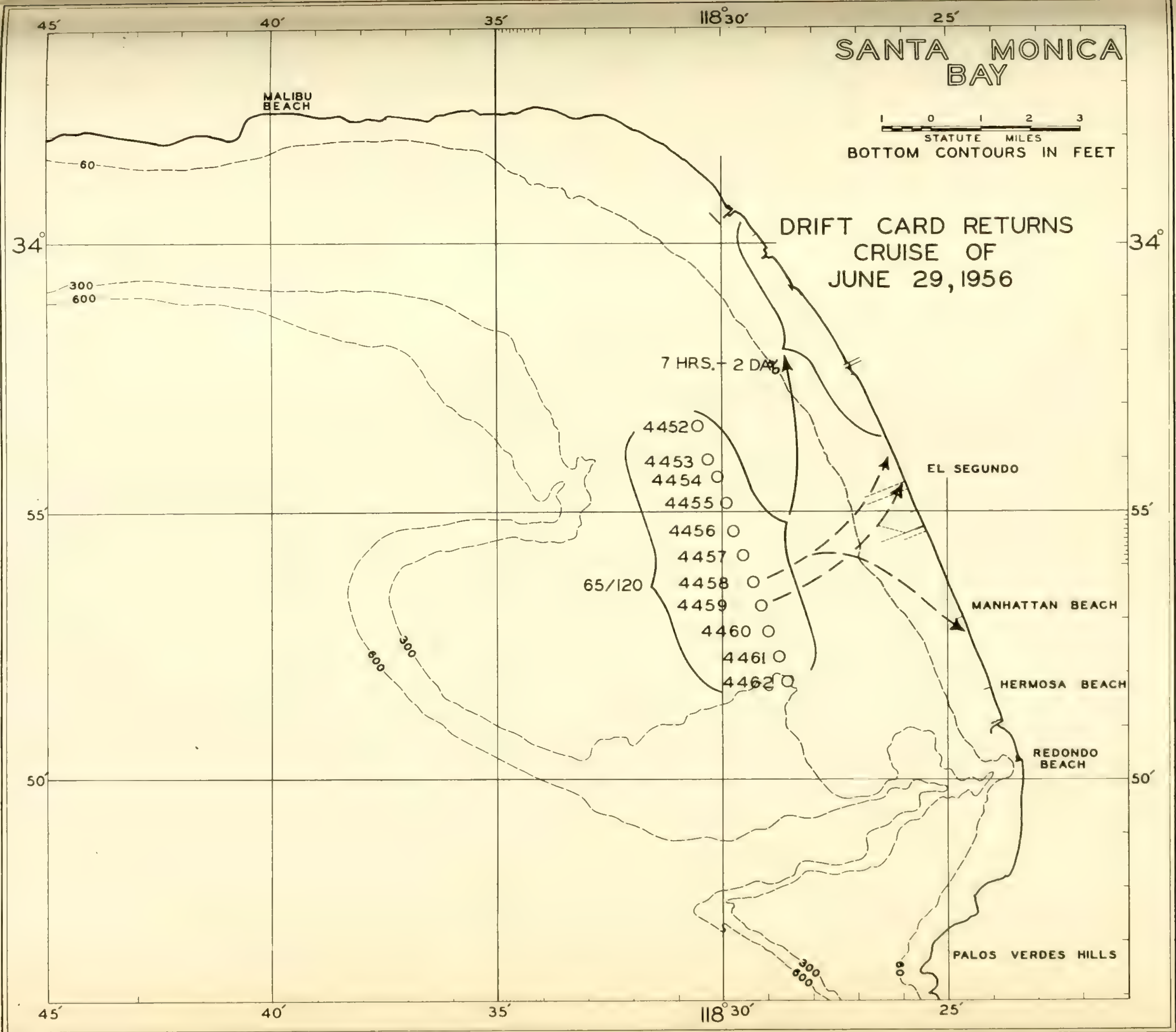
TABLE XI

MAXIMUM VELOCITIES OF DRIFT CARDS

JUNE 19, 1956

Station	Area of Recovery	Distance Travelled	Time of Travel	Velocity Miles/day	Velocity MPH
4297	Palos Verdes Bluff Cove	1 3/4 1½	2¼ 3	18½ 12	0.78 0.50
4298	Malaga Cove (10 cards)	3½-3 3/4	7¼-10¼	12½- 8½	0.52- 0.34
4304	El Segundo	5	18	6½	0.28
4308	Hermosa (2) El Segundo to Hermosa (11)	7½ 5½-7½	18½ 25-31½	9 3/4 4¼-5¼	0.41 0.18- 0.22
4311	Santa Monica to Playa del Rey	5½-9	20-28	6½- 7 3/4	0.27 0.32

Figure 106. Drift card returns, June 29, 1956


SANTA MONICA BAY
STATUTE MILES
BOTTOM CONTOURS IN FEET
DRIFT CARD RETURNS
CRUISE OF
JUNE 29, 1956
MALIBU BEACH
EL SEGUNDO
MANHATTAN BEACH
HERMOSA BEACH
REDONDO BEACH
PALOS VERDES HILLS
7 HRS. - 2 DAYS
4452
4453
4454
4455
4456
4457
4458
4459
4460
4461
4462
65/120
60
300
600
34°
55′
50′
45′
40′
35′
118°30′
25′

following release. On the night of July 26 between 9 p.m. and 1 a.m., 491 cards were released. The station lines on this and subsequent cruises were spaced slightly farther apart to include more of the northern part of the bay. A total of 227, or 45%, were recovered.

Once more the predominant drift was toward the shore with a moderate trend to the south (Figs. 107 and 108). Some cards from the lower stations escaped through San Pedro Channel. However, there was no evidence of a divergence in the central part of the bay or of a westward drift in the Malibu region.

From Station 4474, 4 returns gave velocities of 4 to 4 3/4 miles per day (0.16 - 0.20 MPH), but there was one whose velocity was $12\frac{1}{2}$ miles per day (0.52 MPH). From Station 4475, 2 cards gave velocities of $6\frac{1}{2}$ and $12\frac{1}{2}$ miles per day (0.25 and 0.52 MPH), and one anamolous card gave $16\frac{1}{4}$ miles per day (0.68 MPH).

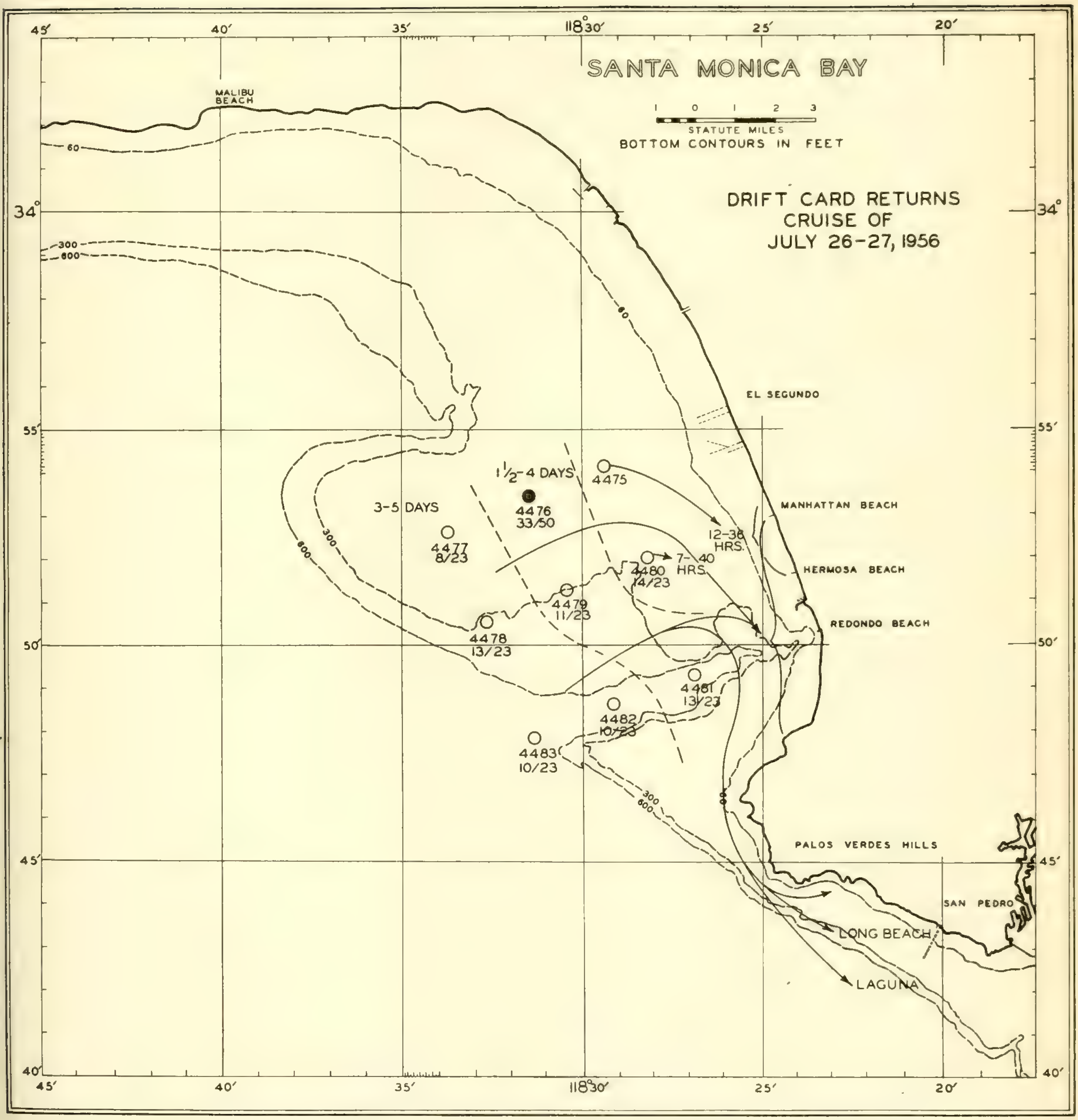
<u>Cruise of August 9-10, 1956</u>

The current pattern on August 9-10 (Figs. 109, 110, and 111) was much like the one on the previous cruise, in that the cards drifted toward the shore. Only two differences in pattern were evident. There was some divergence in the central part of the bay with a weak northerly branch, and the drift to the south in the lower and offshore portions of the bay was much better developed. This southerly trend is well illustrated by the lack of returns from Stations 4507, 4508, and the three returns from 4513 (Long Beach to Huntington Beach), in the lower offshore portion, and by the fact that

Figure 107. Drift card returns, July 26-27, 1956

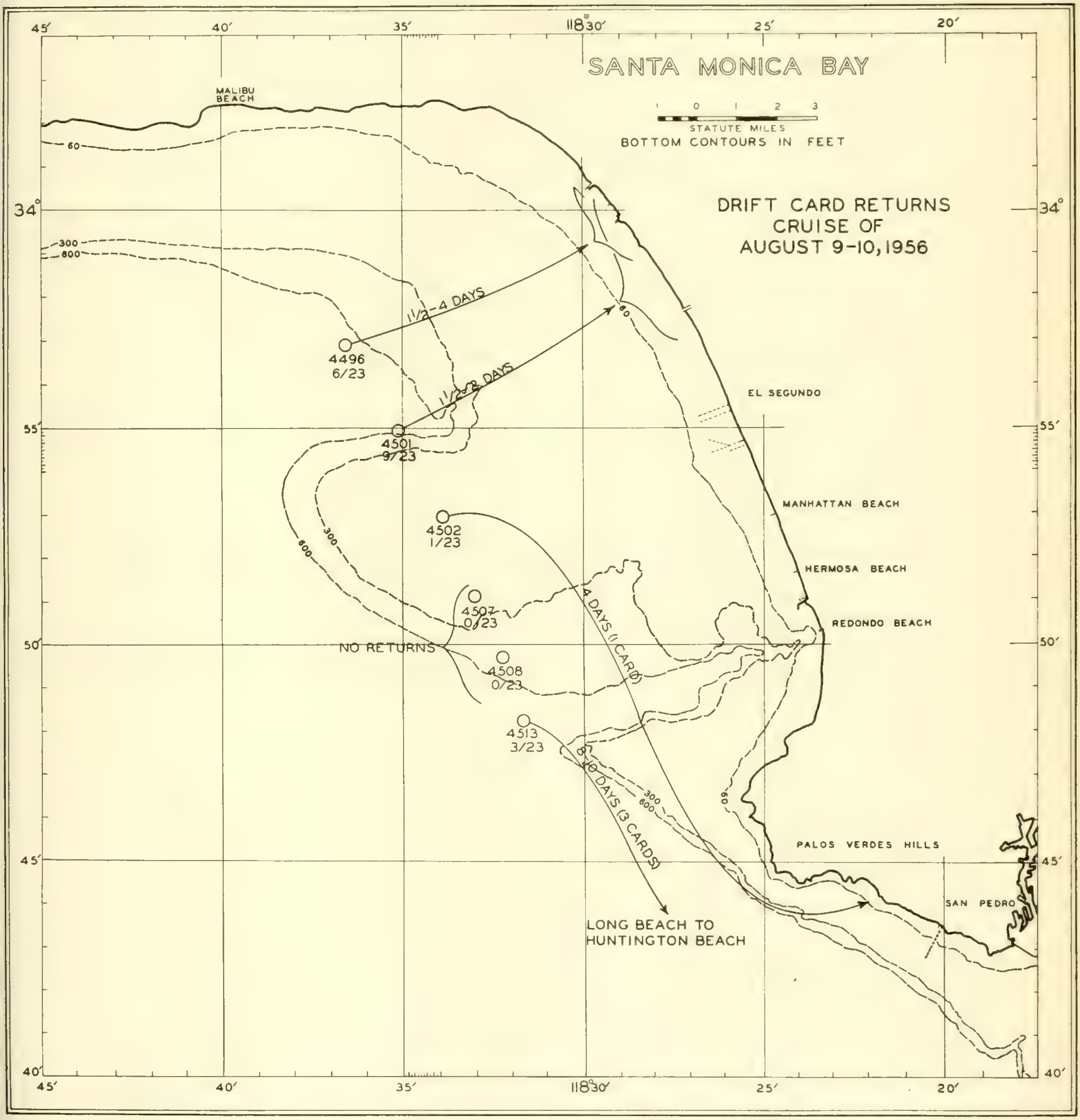

SANTA MONICA BAY
1 0 1 2 3
STATUTE MILES
BOTTOM CONTOURS IN FEET
DRIFT CARD RETURNS
CRUISE OF
JULY 26-27, 1956
MALIBU BEACH
EL SEGUNDO
MANHATTAN BEACH
HERMOSA BEACH
REDONDO BEACH
PALOS VERDES HILLS
4465 9/24
4466 10/23
4467 4/23
4468 5/23
4469 6/23
4470 10/23
4471 15/24
4472 5/23
4473 29/50
4474 9/21
1-2 DAYS
1½-2 DAYS
3 DAYS
60
300
600
45′
40′
35′
118°30′
25′
34°
55′
50′

Figure 108. Drift card returns, July 26-27, 1956



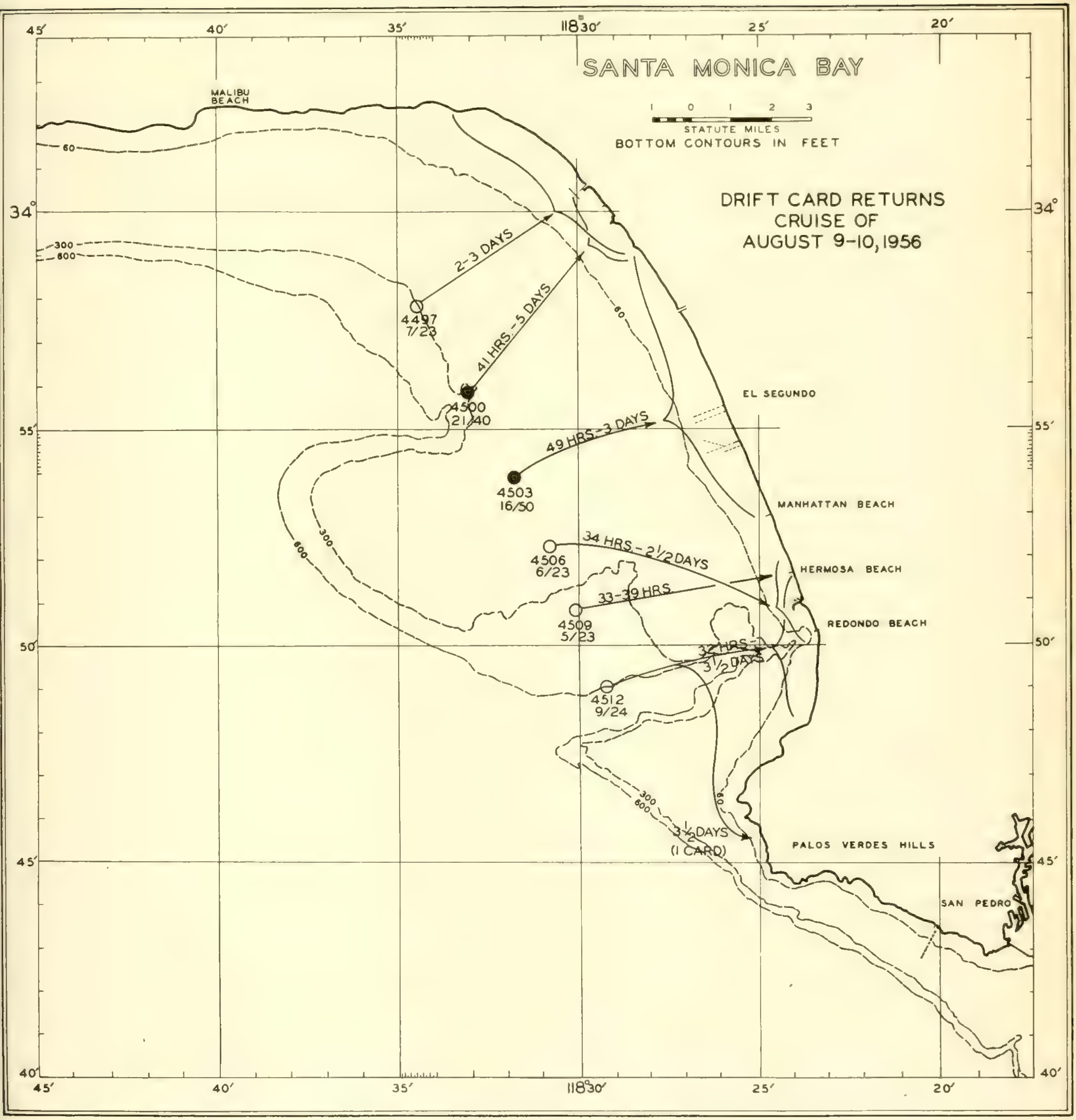
SANTA MONICA BAY
1 0 1 2 3
STATUTE MILES
BOTTOM CONTOURS IN FEET
DRIFT CARD RETURNS
CRUISE OF
JULY 26-27, 1956
45′
40′
35′
118°30′
25′
20′
34°
55′
50′
45′
40′
MALIBU BEACH
EL SEGUNDO
MANHATTAN BEACH
HERMOSA BEACH
REDONDO BEACH
PALOS VERDES HILLS
SAN PEDRO
LONG BEACH
LAGUNA
60
300
600
1½-4 DAYS
3-5 DAYS
4475
4476
33/50
4477
8/23
4478
13/23
4479
11/23
4480
14/23
4481
13/23
4482
10/23
4483
10/23
12-36
HRS.
7-40
HRS.

Figure 109. Drift card returns, August 9-10, 1956



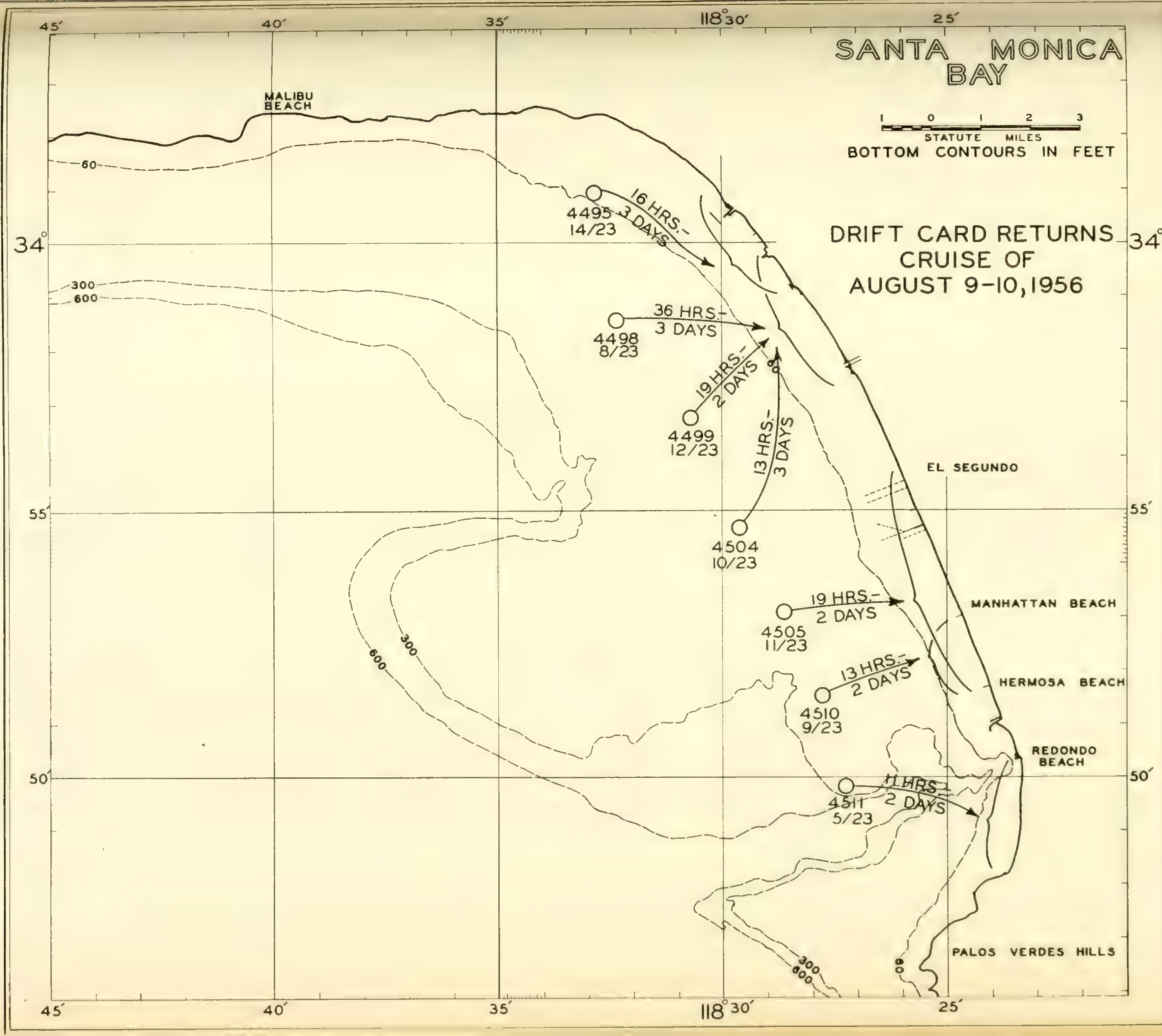
SANTA MONICA BAY
STATUTE MILES
0 1 2 3
BOTTOM CONTOURS IN FEET
DRIFT CARD RETURNS
CRUISE OF
AUGUST 9-10, 1956
MALIBU BEACH
EL SEGUNDO
MANHATTAN BEACH
HERMOSA BEACH
REDONDO BEACH
PALOS VERDES HILLS
SAN PEDRO
4496
6/23
1 1/2-4 DAYS
4501
9/23
1 1/2-2 DAYS
4502
1/23
4 DAYS (1 CARD)
4507
0/23
4508
0/23
NO RETURNS
4513
3/23
8-10 DAYS (3 CARDS)
LONG BEACH TO
HUNTINGTON BEACH
45′
40′
35′
118°30′
25′
20′
34°
55′
50′
45′
40′
60
300
600

Figure 110. Drift card returns, August 9-10, 1956



SANTA MONICA BAY
STATUTE MILES
BOTTOM CONTOURS IN FEET
DRIFT CARD RETURNS
CRUISE OF
AUGUST 9-10, 1956
MALIBU BEACH
EL SEGUNDO
MANHATTAN BEACH
HERMOSA BEACH
REDONDO BEACH
PALOS VERDES HILLS
SAN PEDRO
2-3 DAYS
4497
7/23
41 HRS.-5 DAYS
4500
21/40
49 HRS.-3 DAYS
4503
16/50
34 HRS.-2 1/2 DAYS
4506
6/23
33-39 HRS.
4509
5/23
32 HRS.-3 1/2 DAYS
4512
9/24
3 1/2 DAYS
(1 CARD)
118°30′
34°
55′
50′
45′
40′

Figure 111. Drift card returns, August 9-10, 1956


SANTA MONICA BAY
STATUTE MILES
1 0 1 2 3
BOTTOM CONTOURS IN FEET
DRIFT CARD RETURNS
CRUISE OF
AUGUST 9-10,1956
MALIBU BEACH
EL SEGUNDO
MANHATTAN BEACH
HERMOSA BEACH
REDONDO BEACH
PALOS VERDES HILLS
4495 14/23
16 HRS.- 3 DAYS
4498 8/23
36 HRS.- 3 DAYS
4499 12/23
19 HRS.- 2 DAYS
4504 10/23
13 HRS.- 3 DAYS
4505 11/23
19 HRS.- 2 DAYS
4510 9/23
13 HRS.- 2 DAYS
4511 5/23
11 HRS.- 2 DAYS
60
300
600
34°
55′
50′
45′
40′
35′
118°30′
25′

only one card from Station 4502 was picked up (near Portuguese Bend).

A total of 491 cards were released, of which 154 (31%) have been returned. At the time of writing returns were still incomplete, but the number of recoveries is sufficient to make it improbable that any important departure from this description will occur.

Maximum drift velocities were from three inshore (3-mile) stations, 4495, 4504, and 4510 and amounted to 5 3/4 to 6 3/4 miles per day (0.24 - 0.28 MPH).

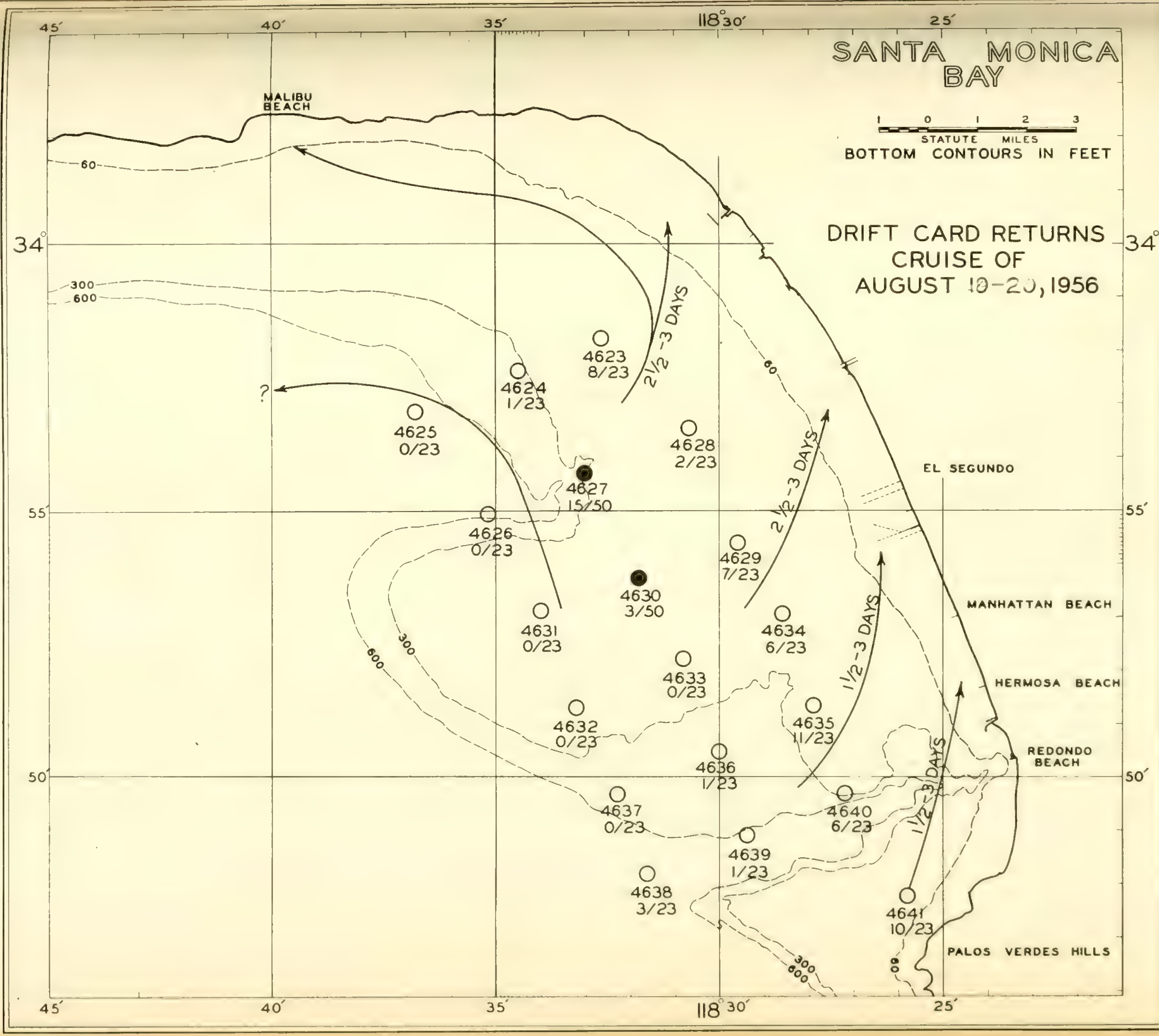
Cruise of August 20-21, 1956

At the time this report was written returns were incomplete, 52 cards out of 491 having been recovered. However, all of these returns are consistent in showing a strong northerly trend (Fig. 112) with no evidence of divergence. Many cards, particularly those from the outer stations, were returned from the Malibu area. Two recoveries were made about 30 hours after release, and all others were at least 48 hours after release (including 15 from the sludge station and 3 from the effluent station). Maximum velocities were 8 miles in 30 hours, or 0.27 MPH from Station 4638 on the southernmost line of stations, and all others were less than 0.17 MPH.

Drift Card Results from Sludge and Effluent Outfall Stations

Current directions and velocities from the sludge and effluent outfall stations are of particular interest. For this reason they are discussed separately in this section. Results from each cruise are presented in Figures 113 to 125, inclusive.

Figure 112. Drift card returns, August 20-21, 1956



SANTA MONICA BAY
STATUTE MILES
BOTTOM CONTOURS IN FEET
DRIFT CARD RETURNS
CRUISE OF
AUGUST 10-20, 1956
MALIBU BEACH
EL SEGUNDO
MANHATTAN BEACH
HERMOSA BEACH
REDONDO BEACH
PALOS VERDES HILLS
2 1/2 -3 DAYS
2 1/2 -3 DAYS
1 1/2 -3 DAYS
1 1/2 -3 DAYS
4623 8/23
4624 1/23
4625 0/23
4626 0/23
4627 15/50
4628 2/23
4629 7/23
4630 3/50
4631 0/23
4632 0/23
4633 0/23
4634 6/23
4635 11/23
4636 1/23
4637 0/23
4638 3/23
4639 1/23
4640 6/23
4641 10/23

Figure 113. Drift card returns from sludge and effluent outfall stations, September 8, 1955.

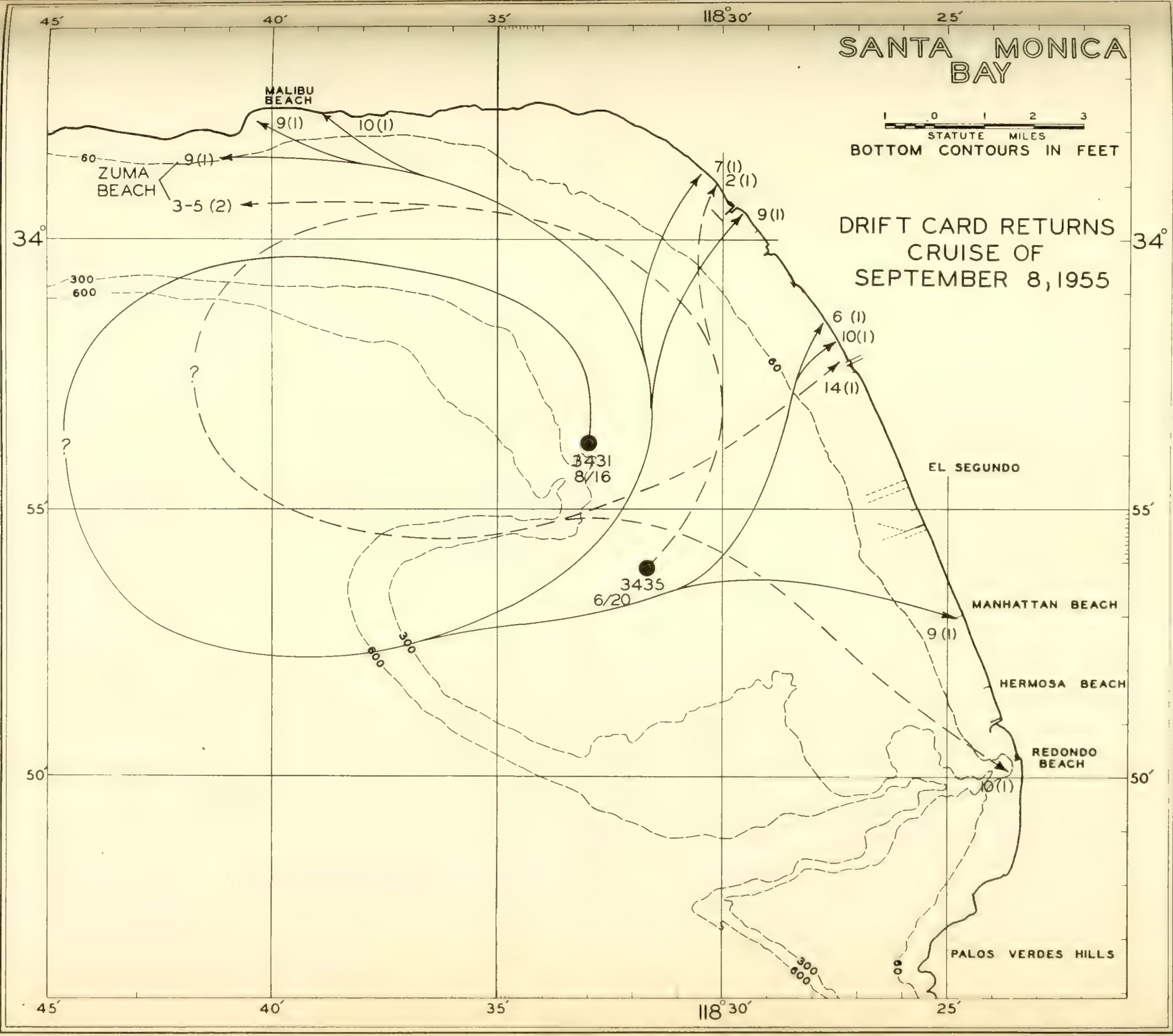

SANTA MONICA BAY
STATUTE MILES
1 0 1 2 3
BOTTOM CONTOURS IN FEET
DRIFT CARD RETURNS
CRUISE OF
SEPTEMBER 8, 1955
MALIBU BEACH
ZUMA BEACH
EL SEGUNDO
MANHATTAN BEACH
HERMOSA BEACH
REDONDO BEACH
PALOS VERDES HILLS
3431
8/16
3435
6/20
9(1)
10(1)
9(1)
3-5 (2)
7(1)
2(1)
9(1)
6 (1)
10(1)
14(1)
9(1)
10(1)
60
300
600
?
34°
55′
50′
45′
40′
35′
118°30′
25′

Figure 114. Drift card returns from sludge and effluent outfall stations, September 29, 1955.


SANTA MONICA BAY
STATUTE MILES
BOTTOM CONTOURS IN FEET
DRIFT CARD RETURNS
CRUISE OF
SEPTEMBER 29, 1956
MALIBU BEACH
EL SEGUNDO
MANHATTAN BEACH
24 HRS. 1 CARD
HERMOSA BEACH
REDONDO BEACH
PALOS VERDES HILLS
3520
7/20
3517
15/20
3-4
3
2-4
60
300
600
34°
55'
50'
45'
40'
35'
118°30'
25'

Figure 115. Drift card returns from sludge and effluent outfall stations, December 29, 1955.

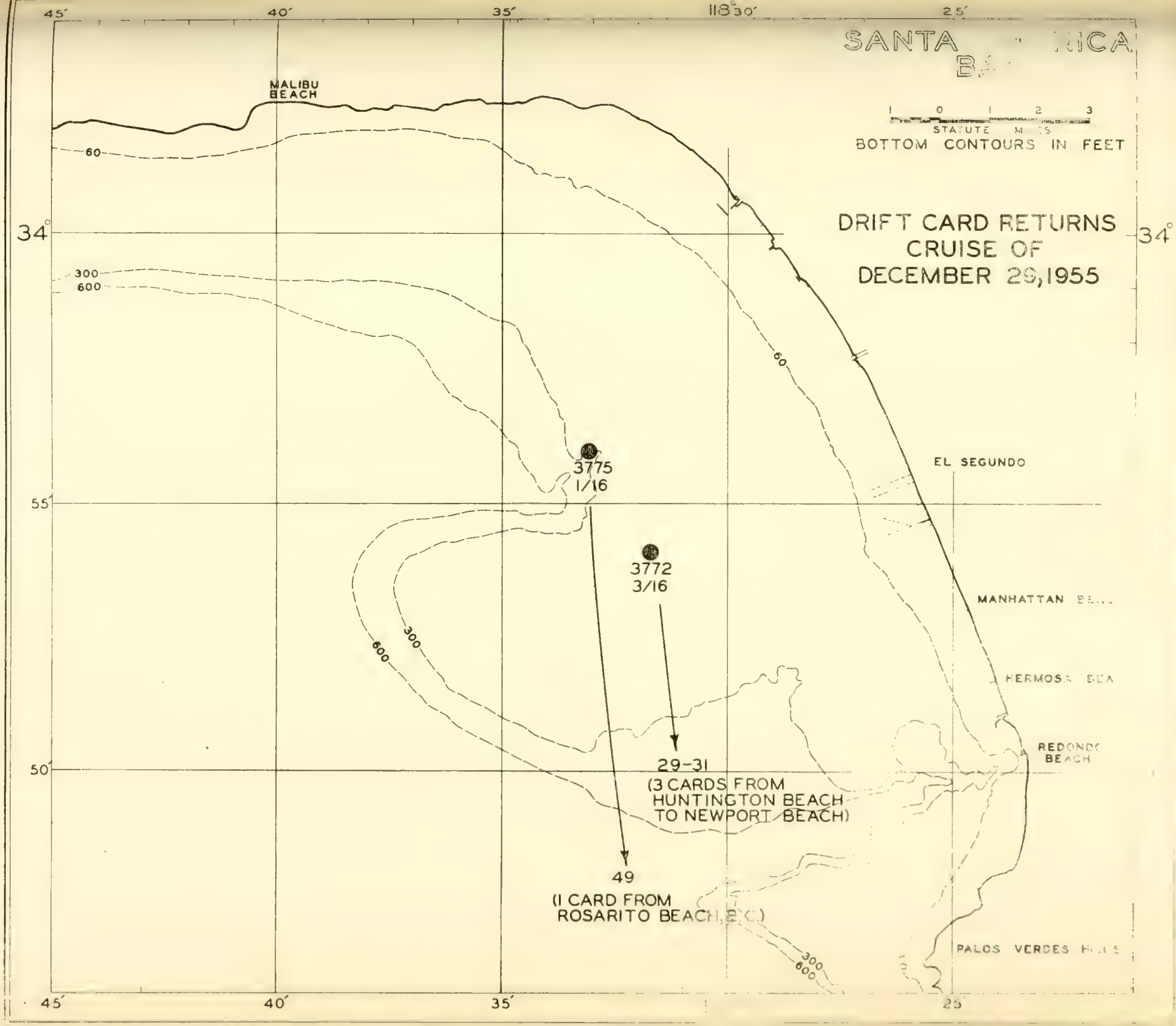

DRIFT CARD RETURNS
CRUISE OF
DECEMBER 29,1955
SANTA
BOTTOM CONTOURS IN FEET
1 0 1 2 3
STATUTE
MALIBU BEACH
EL SEGUNDO
MANHATTAN
REDONDO BEACH
PALOS VERDES
3775
1/16
3772
3/16
29-31
(3 CARDS FROM
HUNTINGTON BEACH
TO NEWPORT BEACH)
49
(1 CARD FROM
ROSARITO BEACH,
60
300
600
118°30'
25'
35'
40'
45'
34°
55'
50'

Figure 116. Drift card returns from sludge and effluent outfall stations, January 18, 1956.

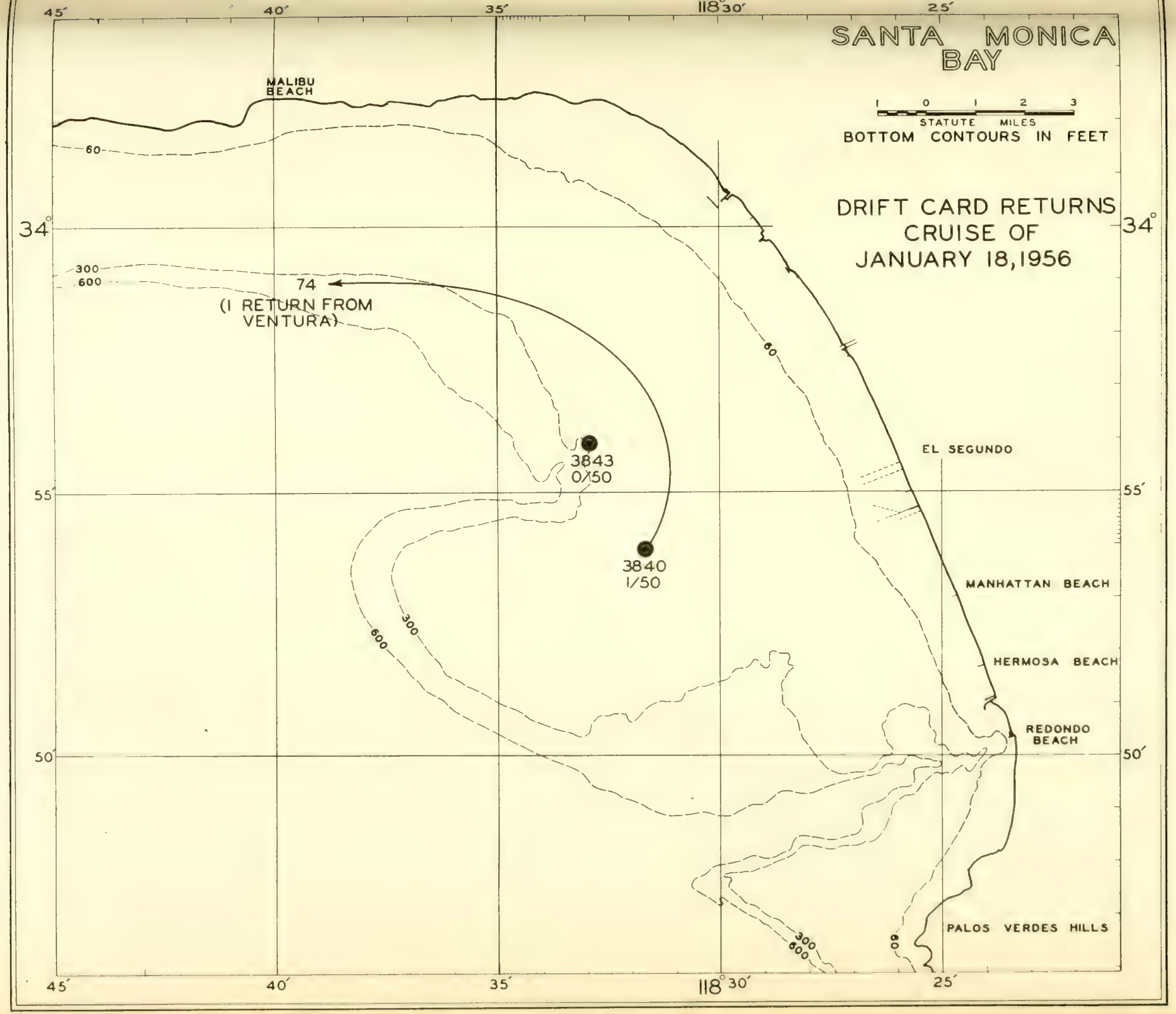

SANTA MONICA BAY
STATUTE MILES
1 0 1 2 3
BOTTOM CONTOURS IN FEET
DRIFT CARD RETURNS
CRUISE OF
JANUARY 18, 1956
MALIBU BEACH
EL SEGUNDO
MANHATTAN BEACH
HERMOSA BEACH
REDONDO BEACH
PALOS VERDES HILLS
74
(1 RETURN FROM VENTURA)
3843
0/50
3840
1/50
60
300
600
34°
55′
50′
45′
40′
35′
118°30′
25′

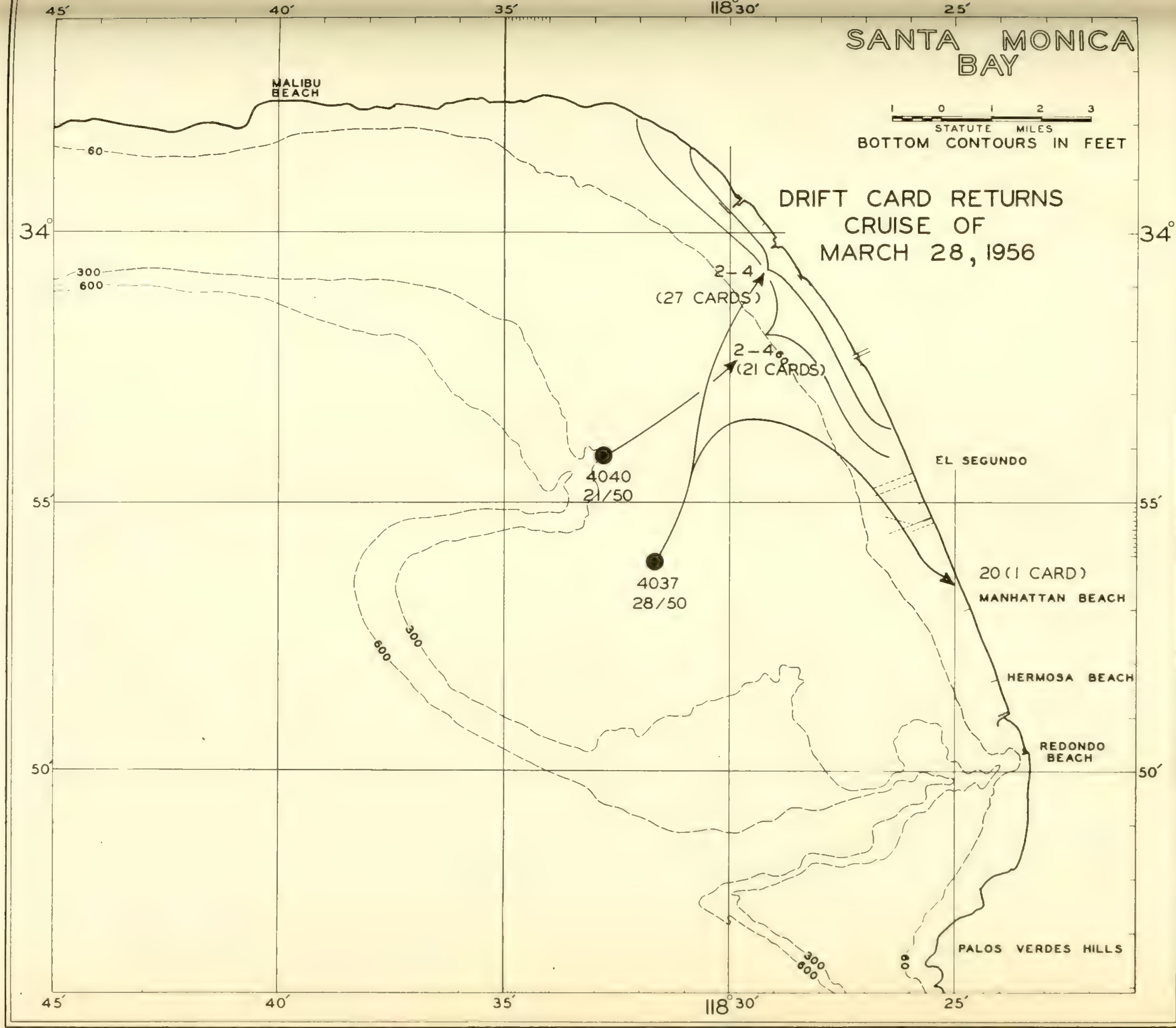
Figure 117. Drift card returns from sludge and effluent outfall stations, February 16, 1956.


SANTA MONICA BAY
STATUTE MILES
BOTTOM CONTOURS IN FEET
DRIFT CARD RETURNS
CRUISE OF
FEBRUARY 16, 1956
MALIBU BEACH
EL SEGUNDO
MANHATTAN BEACH
HERMOSA BEACH
REDONDO BEACH
PALOS VERDES HILLS
3931
1/20
3932
0/20
16
(1 RETURN FROM
PALOS VERDES ESTATES)
60
300
600
34°
55′
50′
45′
40′
35′
118°30′
25′

Figure 118. Drift card returns from sludge and effluent outfall stations, February 22, 1956.

SANTA MONICA BAY
1 0 1 2 3
STATUTE MILES
BOTTOM CONTOURS IN FEET
DRIFT CARD RETURNS
CRUISE OF
FEBRUARY 22, 1956
4 (1 CARD)
(2-3 8 CARDS)
3947
9/23
3944
7/23
2-3
MALIBU BEACH
EL SEGUNDO
MANHATTAN BEACH
HERMOSA BEACH
REDONDO BEACH
PALOS VERDES HILLS
60
300
600
45′
40′
35′
118°30′
25′
34°
55′
50′

Figure 119. Drift card returns from sludge and effluent outfall stations, March 28, 1956.



SANTA MONICA BAY
STATUTE MILES
BOTTOM CONTOURS IN FEET
DRIFT CARD RETURNS
CRUISE OF
MARCH 28, 1956
MALIBU BEACH
EL SEGUNDO
MANHATTAN BEACH
HERMOSA BEACH
REDONDO BEACH
PALOS VERDES HILLS
2-4
(27 CARDS)
2-4
(21 CARDS)
20 (1 CARD)
4040
21/50
4037
28/50
60
300
600
34°
55'
50'
45'
40'
35'
118°30'
25'

Figure 120. Drift card returns from sludge and effluent outfall stations, April 25, 1956.

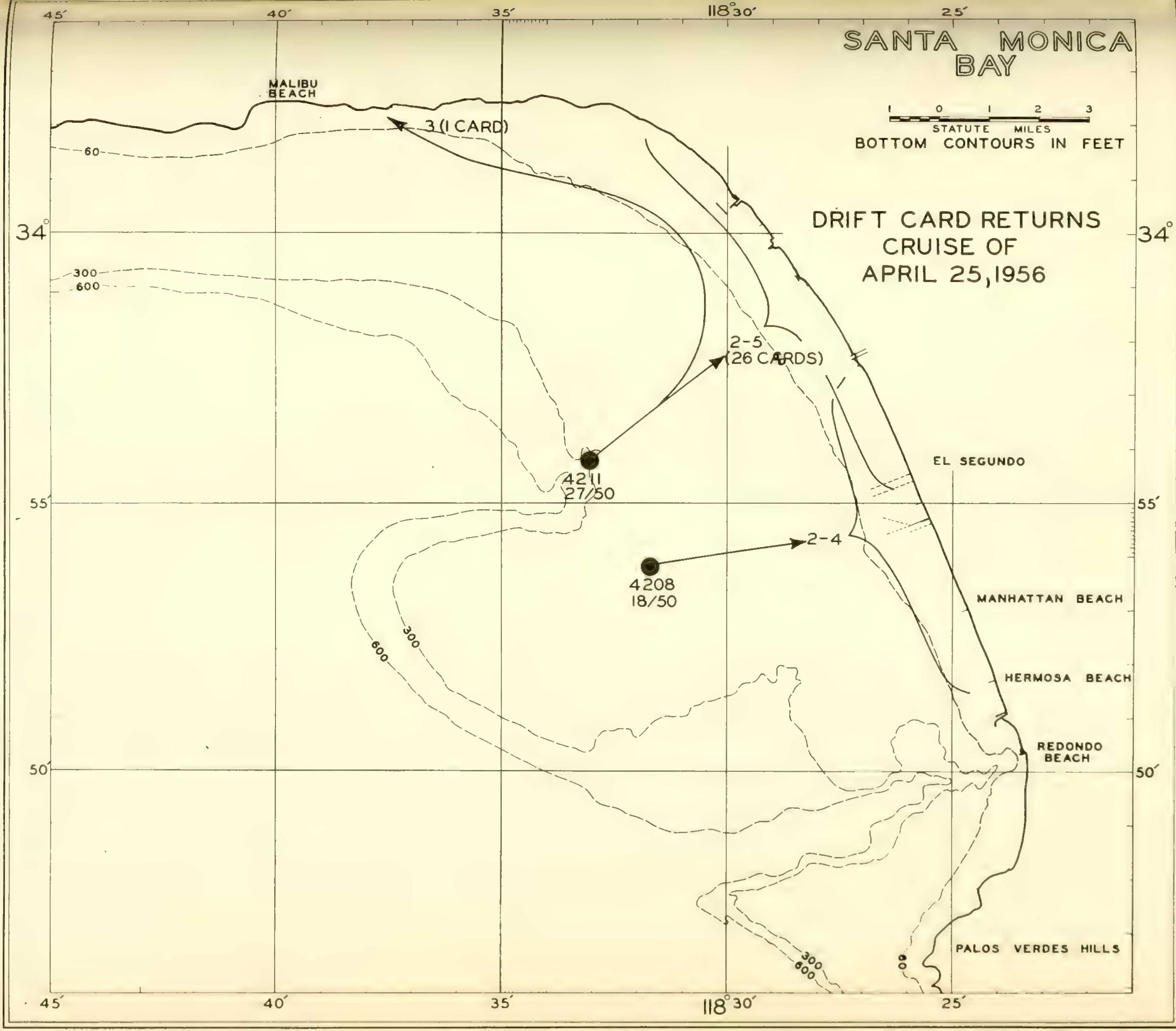

SANTA MONICA BAY
STATUTE MILES
BOTTOM CONTOURS IN FEET
DRIFT CARD RETURNS
CRUISE OF
APRIL 25,1956
MALIBU BEACH
3 (1 CARD)
2-5 (26 CARDS)
4211 27/50
2-4
4208 18/50
EL SEGUNDO
MANHATTAN BEACH
HERMOSA BEACH
REDONDO BEACH
PALOS VERDES HILLS
60
300
600
34°
55′
50′
45′
40′
35′
118°30′
25′

Figure 121. Drift card returns from sludge and effluent outfall stations, May 23-24, 1956.

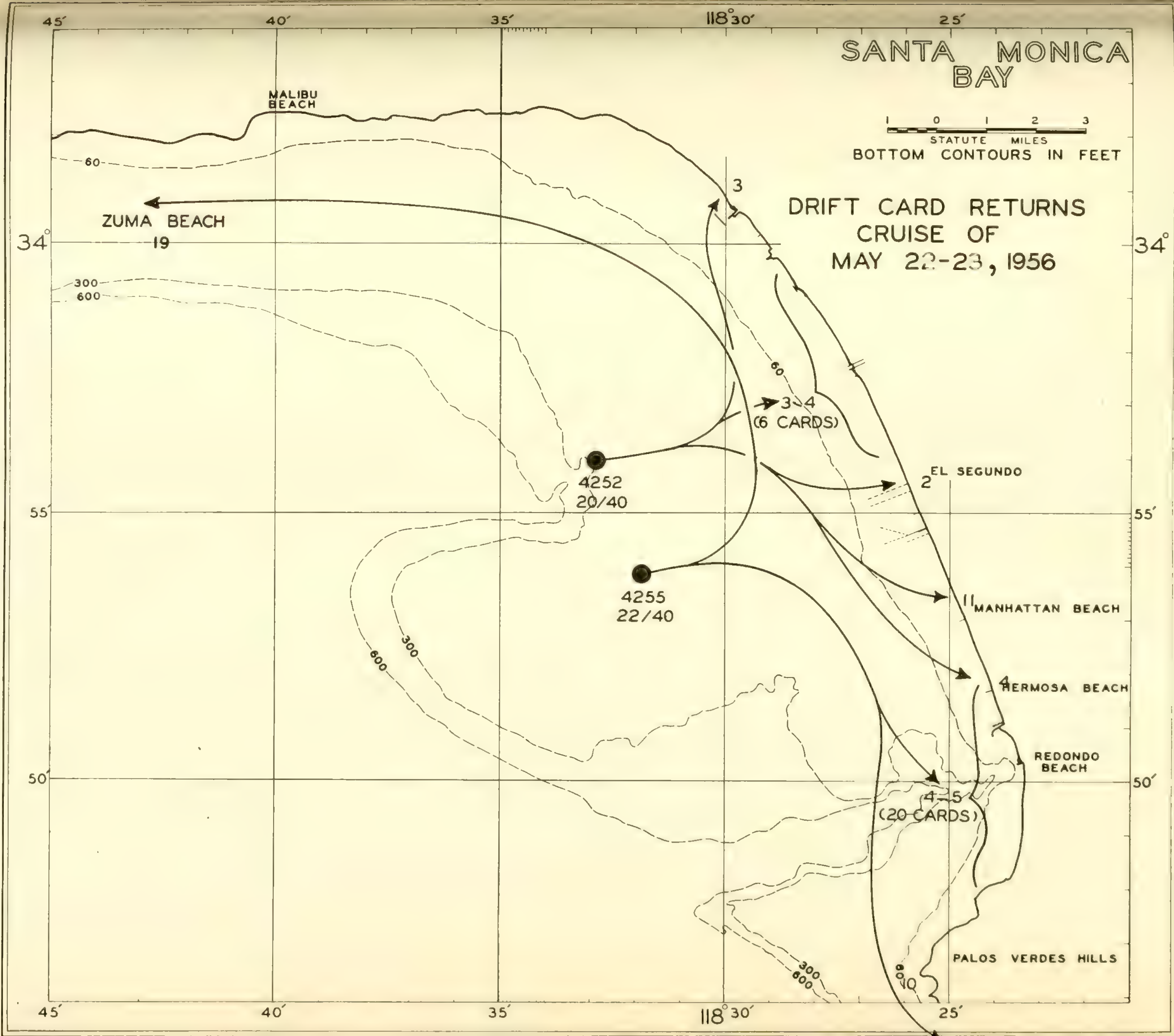

SANTA MONICA BAY
STATUTE MILES
1 0 1 2 3
BOTTOM CONTOURS IN FEET
DRIFT CARD RETURNS
CRUISE OF
MAY 22-23, 1956
MALIBU BEACH
ZUMA BEACH
19
3
3-4
(6 CARDS)
4252
20/40
4255
22/40
2
EL SEGUNDO
11
MANHATTAN BEACH
4
HERMOSA BEACH
REDONDO BEACH
4-5
(20 CARDS)
PALOS VERDES HILLS
60
300
600
45′
40′
35′
118°30′
25′
34°
55′
50′

Figure 122. Drift card returns from sludge and effluent outfall stations, June 19, 1956.

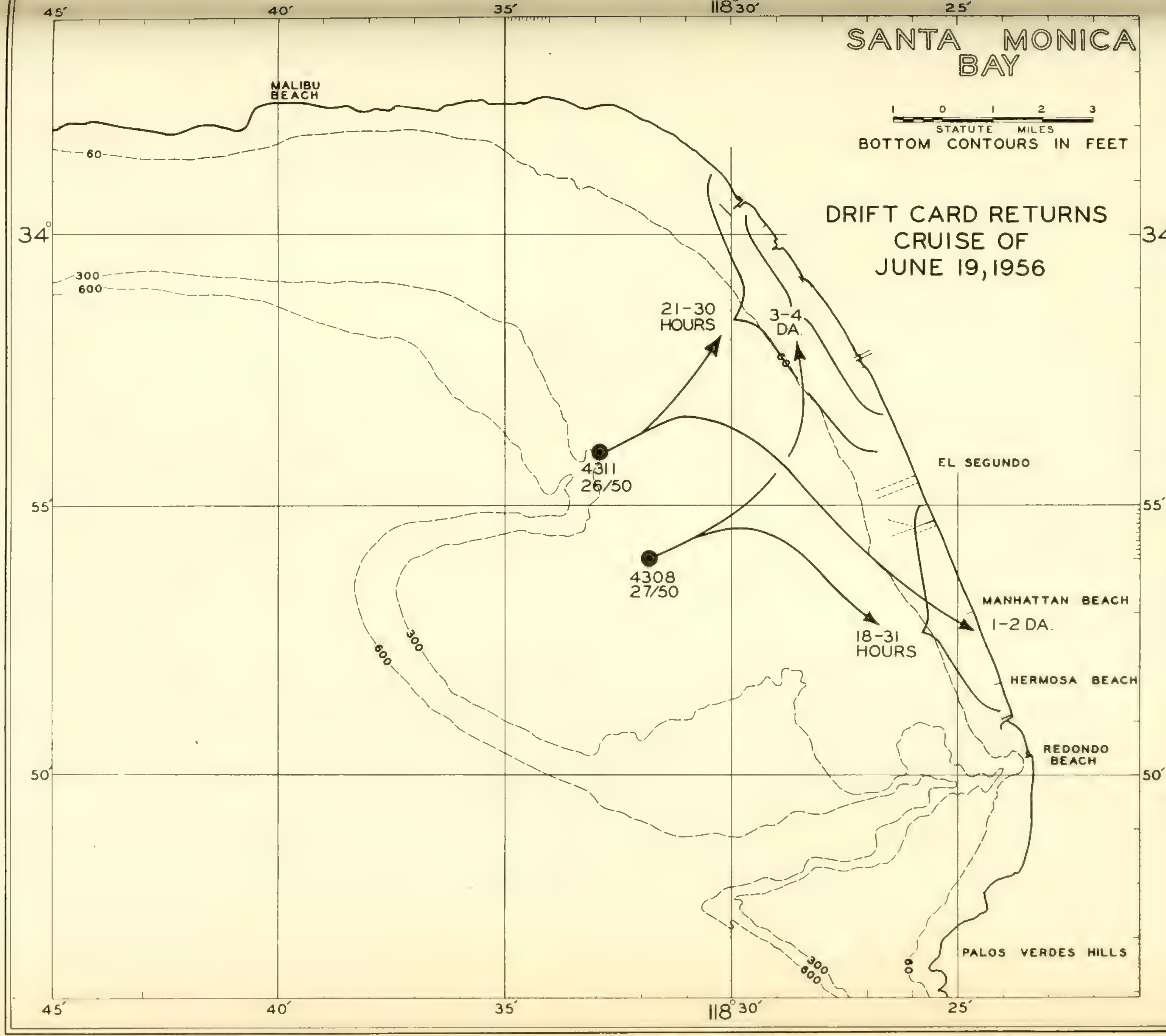

SANTA MONICA BAY
BOTTOM CONTOURS IN FEET
STATUTE MILES
1 0 1 2 3
DRIFT CARD RETURNS
CRUISE OF
JUNE 19, 1956
MALIBU BEACH
EL SEGUNDO
MANHATTAN BEACH
HERMOSA BEACH
REDONDO BEACH
PALOS VERDES HILLS
21-30 HOURS
3-4 DA.
1-2 DA.
18-31 HOURS
4311 26/50
4308 27/50
60
300
600
34°
55′
50′
45′
40′
35′
118°30′
25′

Figure 123. Drift card returns from sludge and effluent outfall stations, July 26-27, 1956.

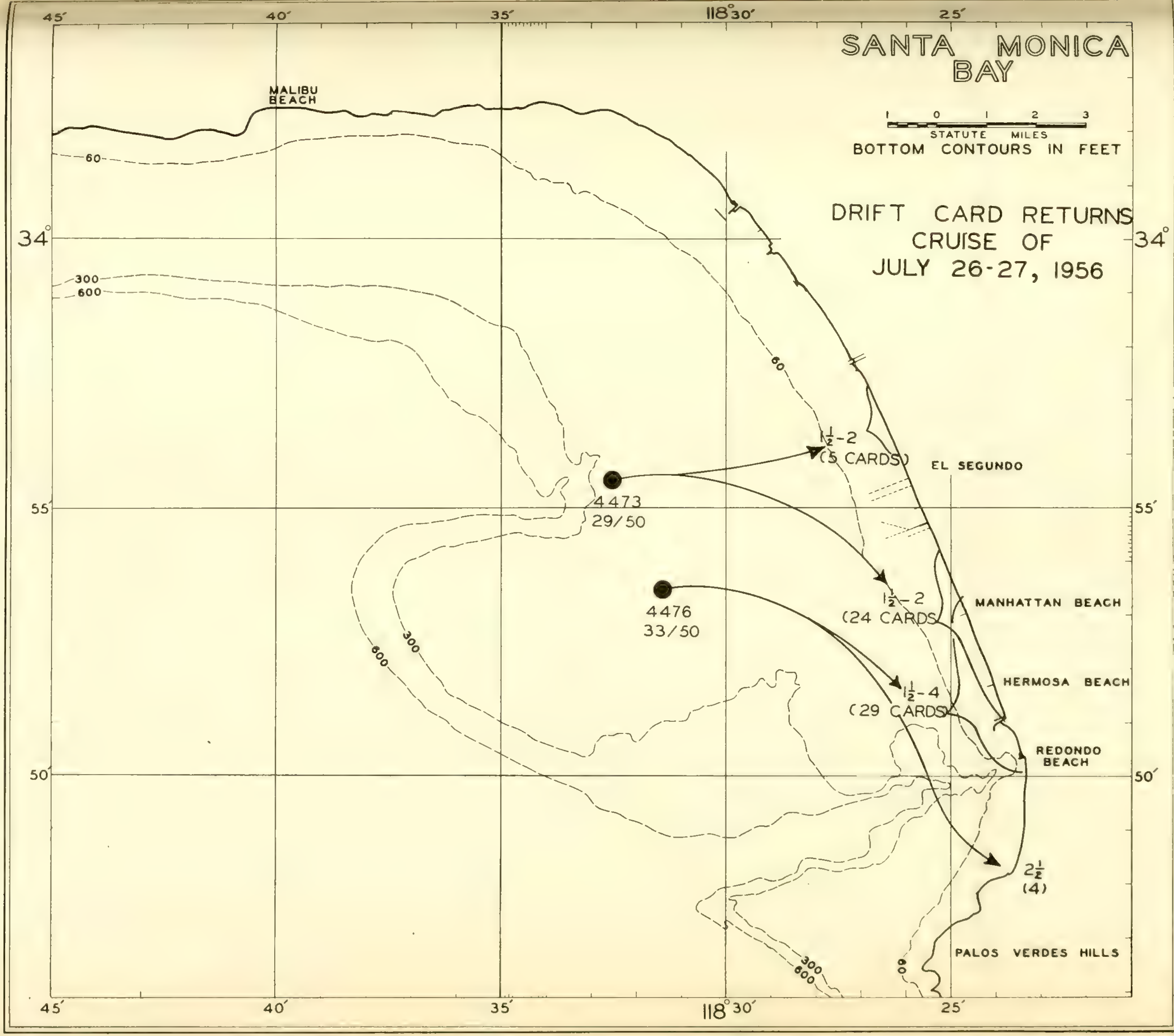
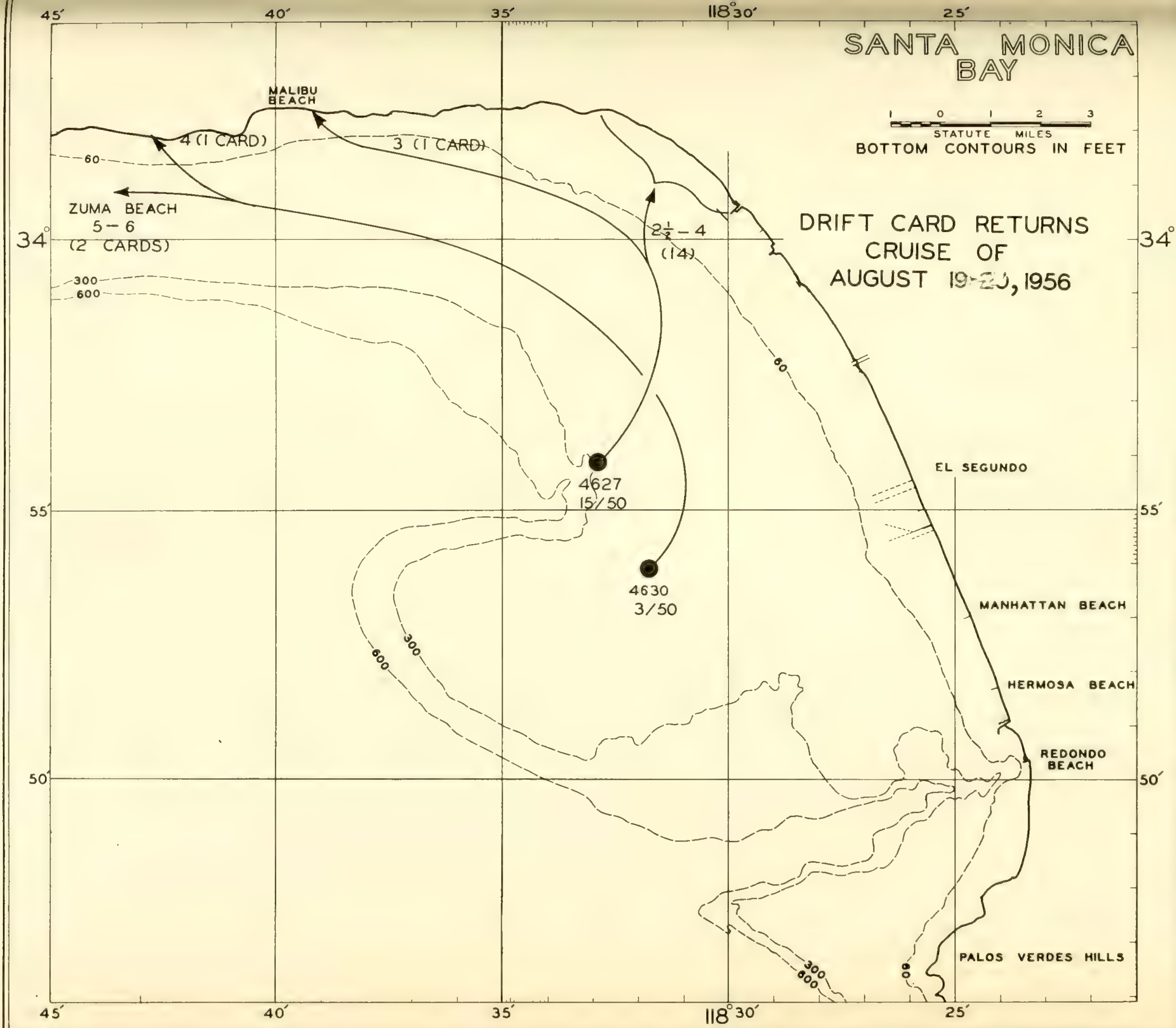

SANTA MONICA BAY
STATUTE MILES
BOTTOM CONTOURS IN FEET
DRIFT CARD RETURNS
CRUISE OF
JULY 26-27, 1956
MALIBU BEACH
EL SEGUNDO
MANHATTAN BEACH
HERMOSA BEACH
REDONDO BEACH
PALOS VERDES HILLS
4473
29/50
4476
33/50
$1\frac{1}{2}$-2
(5 CARDS)
$1\frac{1}{2}$-2
(24 CARDS)
$1\frac{1}{2}$-4
(29 CARDS)
$2\frac{1}{2}$
(4)
34°
55'
50'
45'
40'
35'
118°30'
25'

Figure 124. Drift card returns from sludge and effluent outfall stations, August 9-10, 1956.


SANTA MONICA BAY
STATUTE MILES
BOTTOM CONTOURS IN FEET
DRIFT CARD RETURNS
CRUISE OF
AUGUST 9-10, 1956
MALIBU BEACH
EL SEGUNDO
MANHATTAN BEACH
HERMOSA BEACH
REDONDO BEACH
PALOS VERDES HILLS
41 HRS.-5 DAYS
37-58 HRS.
4500
21/50
4503
16/50
118°30′
34°
55′
50′
45′
40′
35′
25′
60
300
600

Figure 125. Drift card returns from sludge and effluent outfall stations, August 20-21, 1956.


SANTA MONICA BAY
STATUTE MILES
BOTTOM CONTOURS IN FEET
DRIFT CARD RETURNS
CRUISE OF
AUGUST 19-20, 1956
MALIBU BEACH
4 (1 CARD)
3 (1 CARD)
ZUMA BEACH
5 – 6
(2 CARDS)
2½ – 4
(14)
4627
15/50
4630
3/50
EL SEGUNDO
MANHATTAN BEACH
HERMOSA BEACH
REDONDO BEACH
PALOS VERDES HILLS
60
300
600
34°
55′
50′
45′
40′
35′
118°30′
25′

Between September 9, 1955 and February 16, 1956, five drift card cruises were made. On all but one the cards showed at least an initial drift outside the bay, and on three cruises the surface waters from the outfall areas appeared to have been completely flushed either to the north or to the south. The one exception was the cruise of September 29, on which the cards moved toward shore but at relatively low velocities, generally requiring 48 hours or more to reach the beach. However, a single card from an outfall station on this cruise was reported 24 hours after its release at 1:30 p.m. The next card recovered was 46 hours after release. Anomalous cards of this kind appear not infrequently. It may be suspected that an error was made in recording the date when the card was filled out by the finder, but it should be remarked that in tabulating and discussing drift card results, all cards are taken at face value and none are omitted except those which obviously are impossible (recorded as being recovered two hours before they were released, etc.). The case under discussion is the only one in which a card from an outfall station has assumed such importance. If this card be eliminated, the minimum time of drift to the nearest beach would be about 34 instead of 19 hours.

Beginning February 22, the situation changed and cards from outfall stations on all eight cruises between that date and August 9-10 came inshore with varying velocities. At first the maximum velocities were low, of the order of 2 miles per day, but they increased until on April 25 they were 6 miles per day and again on June 19 from the effluent station they

reached a velocity of 10 miles per day. On the three subsequent cruises, maximum velocities decreased although the direction of flow was still toward the shore. The August 19-20 returns show a strong northerly drift, and suggest a return to conditions encountered during the fall of 1955.

In the interest of clarity, data from all sludge and effluent outfall stations are summarized in Table XII. The date and station numbers are given, together with the principal location of recoveries. Isolated cards which drifted to the north or south of the principal area are not described, although they were not neglected in calculating times of drift or velocities. Under the column headed "Time of Drift" the minimum time from each station is given. For want of a better word, "average" times of drift are also tabulated, but the figures do not represent arithmetic means; they were estimated by inspection of tabulated data and by arriving at a reasonable figure which would give the time of arrival of the first significant group of cards. Wherever the difference between minimum and "average" times of drift is large, it indicates that one or, at most, a few cards arrived well in advance of the first significant groups. Velocities in statute miles per hour are calculated from the paths of drift of individual cards. The last column in the table gives the time that would have been required for the cards to have reached the nearest shore, assuming that the velocities previously determined would apply had the cards drifted directly toward the beach, a distance of approximately 5½ miles. By this method an estimate can be made of the worst

TABLE XII

Cruise	Stations Sludge	Stations Effl.	Principal Location of Recoveries	Time of Drift Min.	Time of Drift Ave.	Velocity (MPH) Max.	Velocity (MPH) Ave.	Time required to reach nearest shore Min.	Time required to reach nearest shore Ave.
Sept. 8	3431		Zuma Beach to Manhattan	6 da.	$8\frac{1}{2}$ da.	x	x	x	x
		3435	Zuma Beach to Redondo	52 hr.	8 da.	0.15	x	28 hr.	x
Sept. 29	3520		Playa del Rey to Manhattan	48 hr.	$3\frac{1}{2}$ da.	0.10	.06	48 hr.	88 hr.
		3517	Manhattan to Torrance Beach	24 hr.	48 hr.	0.29	0.15	19 hr.	36 hr.
Dec. 29	3775		Rosarita Beach, Baja Calif.	17 da.	x	x	x	x	x
		3772	Huntington Beach to Newport	29 da.	30 da.	x	x	x	x
Jan. 18	3843		no returns	x	x	x	x	x	x
		3840	Ventura	74 da.	x	x	x	x	x
Feb. 16	3931		Palos Verdes	16 da.	x	x	x	x	x
		3932	no returns	x	x	x	x	x	x
Feb. 22	3947		Venice to Playa del Rey	45 hr.	60 hr.	0.11	0.08	45 hr.	60 hr.
		3944	El Segundo to Hermosa	43 hr.	48 hr.	0.14	0.12	36 hr.	40 hr.
March 28	4040		Topanga Canyon to El Segundo	50 hr.	4 da.	0.12	x	44 hr.	90 hr.
		4037	Santa Monica to El Segundo	49 hr.	4 da.	0.12	x	45 hr.	90 hr.
April 25	4211		Malibu, Santa Monica & El Segundo	40 hr.	72 hr.	0.18	0.08	$28\frac{1}{2}$ hr.	66 hr.
		4208	Playa del Rey to Redondo	29 hr.	63 hr.	0.24	0.12	23 hr.	46 hr.
May 22-23	4252		Santa Monica to Manhattan	45 hr.	72 hr.	0.14	0.09	40 hr.	61 hr.
		4255	Hermosa to Flat Rock Point	62 hr.	84 hr.	0.12	0.10	45 hr.	55 hr.

(continued)

TABLE XII (continued)

Cruise	Stations		Principal Location of Recoveries	Time of Drift		Velocity (MPH)		Time required to reach nearest shore	
	Sludge	Effl.		Min.	Ave.	Max.	Ave.	Min.	Ave.
June 19	4311		Santa Monica to El Segundo	21 hr.	25 hr.	0.26	0.22	21 hr.	25 hr.
		4308	Santa Monica to El Segundo, Manhattan to Redondo	18 hr.	30 hr.	0.42	0.23	13 hr.	24 hr.
June 29	no sludge or effluent stations								
July 26-27	4473		Playa del Rey, Manhattan to Redondo	39 hr.	42 hr.	0.21	0.21	27 hr.	27 hr.
		4476	Manhattan to Redondo, Malaga Cove	33 hr.	43 hr.	0.21	0.16	26 hr.	34 hr.
Aug. 9-10	4500		Santa Monica to Playa del Rey	41 hr.	45 hr.	0.14	0.14	39 hr.	39 hr.
		4503	Venice to Manhattan	37 hr.	42 hr.	0.16	0.15	34 hr.	38 hr.
Aug. 19-20	4627	4630	Returns incomplete, as of Aug. 27, 1956	greater than 60 hr.				greater than 48 hr.	

and is of relatively minor significance in the problem at hand. Eddy diffusion, on the contrary, is a process whose importance is exceeded only by its complexity. This does not imply that a discussion of eddy diffusion is without merit or that no further attempt should be made to investigate the phenomenon on both an experimental and a theoretical basis. A thorough investigation of eddy diffusion eventually must be made before assured predictions can be made of the rate of physical dilution of any substances which may be discharged into the sea. This matter is of particular importance to the Los Angeles area, not only because of sewage and industrial waste, but because of the probability that disposal of radioactive waste will certainly become of great concern in the near future.

During the first few months of this survey, an attempt was made to obtain information on the coefficient of eddy diffusivity from drift card returns, and to lay a foundation in case it became necessary later to attack the matter of diffusion as a major issue. For various reasons such a research program was not established. However, it is appropriate to present the results of the preliminary work accomplished.

Twenty analyses of drift card returns were made at stations from which the drift was predominantly toward the shore and from which some estimate could be made as to the radius of the area occupied by the cards. The method used was a modification of that of McEwen (1950), who states that:

$$A = (r_1^2 - r_0^2) / 2\lambda^2 (T_1 - T_0)$$

possible conditions using both maximum and "average" velocities. Whenever the time of drift was greater than about 4 days and the flow was out of the bay, no velocities were computed.

It is believed that the reliability of the information presented here is good. It is true that the actual trajectories of individual cards is not known, but those which showed the greatest velocities were, in nearly all cases, those which came most directly inshore. The distances travelled were measured along a line between the station and the points of recovery, and in those instances where the cards described an arc on their journey, or came inshore and were then carried to the south or north by a littoral current, some error therefore may be introduced. But whenever it appeared that the drift departed significantly from a straight line, a correction factor, arbitrary in each case to be sure, was applied. In short, every consideration was given so that the results, if they erred, would err on the side of increasing velocities. This approach is justified considering the purpose of the survey.

Eddy Diffusion

Sewage discharged into the ocean may be transported by currents, but its dilution with the passage of time can be accomplished only by turbulent mixing and by vertical and horizontal eddy diffusion. In Santa Monica Bay turbulent mixing due to convectional overturn (cooling or evaporation), or to stirring of the waters by strong winds occurs infrequently

Where A is the coefficient of eddy diffusivity, r_0 and r_1 are the radii of the initial and final areas, $\lambda \sim 2.5$, and T_0 and T_1 are the times at the beginning and end of travel.

If r = 0, $T_0 = 0$, and $\lambda = 2.5$, then:

$$A = r_1^2 \;/\; 12.5\ T_1$$

In using this formula as a first approximation to A, r_1 was taken as one-half the length of shore line along which recoveries were made, neglecting those cards which drifted for unreasonably long times or long distances. This involved some judgement as to the distance r_1 beyond which there was no concentration, and it also required that the mass of cards approach the beach at not too small an angle. Whenever the group of cards approached the shore at a more acute angle, a simple method was devised by which both r_1 and T_1 could be estimated, but there was no opportunity to extend the work to include such stations. If the time or distance of drift is long, and only a portion of the cards diffused far enough to reach the shore, the method developed by McEwen for such a case can be used.

Values computed for the coefficient of eddy diffusivity for individual stations ranged from 1.2×10^4 to 6.1×10^5 cm^2/sec. However, most values lay between 4×10^4 and 3×10^5, and the mean value was 1.27×10^5 cm^2/sec. This result is entirely consistent with those obtained by other investigators and by other methods which are summarized by Pearson (1955).

The times of drift varied from 2 to 16 days. The average distances travelled between points of release and the shore were 8 to 13 miles.

In the twenty cases, there was no correlation between the value of the coefficient and either the time of travel or the distance travelled. This is not necessarily contrary to the known variation in the value of A with the scale of the phenomenon, but is simply means that within the limits of accuracy of these computations for A, and within the time or distance scales here involved, no correlation was apparent.

Discussion and Conclusions

The circulation of water within Santa Monica Bay is maintained by a combination of many forces. Among them, not necessarily in order of their importance, are these:

1. General coastal circulation
2. Winds
3. Tides
4. Waves
5. Local thermal conditions

The influence of general coastal circulation certainly is felt within the bay, either as a general northerly or southerly current or perhaps as an eddy, the inshore portion of which may affect the direction and velocity of currents within a few miles of the beaches.

Winds can establish currents either by direct frictional drag or indirectly by setting up density currents due to mass transport of less dense surface water away from, or toward, the shore. Rotary currents in deeper water are associated with tides. Those closer to shore are oscillating currents, moving in and out of the bay or up and down the shore, changing direction with each ebb and flow.

Over most of the bay waves, whether due to local winds or to swell coming from distant storm areas, will result in only a small net transport in their direction of progress, but inshore they play an important role in establishing a littoral drift.

There is some evidence that the large quantities of warm, fresh water introduced into the bay by the Hyperion disposal plant, Ballona Creek, and the two Edison Company steam plants may cause local modifications of flow.

There are no data at present upon which these factors can be satisfactorily isolated and their relative importance determined, but we can deal with observational data which will show variations in net effects.

Surface Film

The behavior of surface films or of floating objects whose bulk lies largely above the surface of the water did not come within the scope of this survey. Neither did the collection of meteorological data upon which predictions of the behavior of such films from the region of the proposed outfalls can be made. The only statement possible is the general one that if an appreciable wind is present, surface films will be transported in the direction of the wind at a velocity greater than that of the water beneath. During periods of relative calm or during periods of strong winds when the surface is broken by extensive white-caps, their drift will correspond more to that of the upper layers of water.

Surface Currents

The main focus of interest probably is in the upper layer of water because it is within this layer that a large part of the effluent and at least part of the sludge initially will be found. They will remain there until they become so diluted by settling of particulate matter and by vertical and horizontal mixing that the waters are no longer recognizable as containing material of sewage origin. It is also in this layer that maximum current velocities generally will be found.

During the period of September 8, 1955 through February 16, 1956, the pattern of surface flow was variable, but the bay appeared to be well flushed, at least intermittently, by relatively strong currents directed either to the north or to the south. Of the five cruises during this interval, on only one (September 29, 1955) was there a general drift to the east and inshore from part of the area. On one (September 8, 1955) the initial drift was to the north and outside the bay, and on the other three the surface waters appeared to have been removed almost completely from the bay (December 29, January 18, and February 16).

Beginning on February 22, and extending through the cruise of August 9-10, 1956, the predominant drift was toward the shores of the bay, but frequently superimposed upon this was a moderate southerly or northerly component. Many of these later cruises, as well as the earlier one of September 29, 1955, showed signs of a divergence in the current as the water approached the shore. It is most clearly marked on the charts showing drift card returns of September 29, Area III, and of

August 9-10, where returns from stations north of a particular line were separated by an evident gap from those below the line. The cruise of August 19-20, 1955, with its strong northward component and low velocities suggest a return to conditions noted in the fall of 1955.

The location of this divergence varied somewhat in position from north to south. Its distance from shore is difficult to estimate, but it usually extended at least to within three miles of shore. Whenever an inshore drift was well developed and a general southerly or northerly component was of no great importance, the divergence appeared to occupy a place generally near the center of the bay.

If the spread of cards from individual stations be examined in detail, there is evidence of a littoral drift close to the shore. Occasionally this spread was greater than could be accounted for by either random dispersal or by the divergence described above, and cards appeared well to the south or to the north of the main group, the time of travel being not much greater. Such cards may well have been carried by a littoral drift in some cases opposite in direction to that of the main current pattern.

The general inshore drift of surface currents in the spring and summer of 1956 has important implications as far as the transport of sewage is concerned. Certainly such a drift is less favorable than a situation in which the currents are directed offshore, because it means that material discharged from the proposed outfalls would have been carried shoreward. However, the direction of flow is not, in itself,

the limiting factor. Given a shoreward transport, the rate of disappearance of coliform organisms then becomes the all-important criteria by which conditions at the beach must be judged. This intimately involves the velocity of transport.

The general statement has been made that current velocities in Santa Monica Bay are relatively slow, but this is not sufficient. Because current velocities are of critical importance, it is necessary to analyze them in more detail.

Current measurements involving the use of current meters, current crosses, and drogues have shown that outside of the littoral zone velocities of the order of 0.6 MPH are rare, those of the order of 0.4 are infrequent, and the usual velocity is 0.2 MPH or less. Current meter observations showed the highest velocities in the Malibu region and near the Redondo Submarine Canyon. Drogues have given values as high as 0.6 MPH in the general region of the proposed outfalls, but it is to be noted that these observations were of drift of a few hours, and the net transport toward the beach would probably have been at a lesser speed over a period of twelve hours or more.

The maximum current velocity obtained from drift card recoveries was 0.78 MPH. However, of the 1,803 cards recovered to date, only those from two cruises showed velocities greater than 0.58 MPH, and the number of individual cards travelling at that speed were few indeed. On only 4 cruises were maximum velocities in excess of 0.31 MPH. Moreover, almost without exception those high velocities were obtained from stations

lying in the southern or inshore stations. For the vast majority of cards a figure of 0.2 MPH is a reasonable average velocity.

More important than the maximum velocities for special regions such as the southern end of the bay, are the data obtained from the stations located at the approximate sites of the proposed sludge and effluent outfalls. Reference is again made to Table XII, in which those data are summarized. In no case was a velocity greater than 0.58 MPH recorded from a sludge or effluent outfall station. The single case of a maximum velocity greater than 0.31 MPH was recorded from the effluent station on June 19, 1956. These figures are significant because the velocities represent the limits within which coliform organisms from primary effluent of the type found at Hyperion will be reduced to legal specifications at the beach. This matter is discussed in detail in the section of the report of the University of Southern California which deals with the bacteria, but the general conclusion is that under the conditions specified, the coliform standards as now established by the State Water Pollution Board probably will be met.

The obvious question now arises, can velocities in excess of those described ever occur at the outfall stations in the central part of the bay? The answer must be in the affirmative. It seems reasonable that under conditions of strong westerly winds, and perhaps rarely under other circumstances, higher velocities may occur. None of our observations were made under storm conditions. Exactly how often this might occur,

in terms of percentage frequency, cannot be stated because there is too little basic information on the relationship between winds and currents in general, and in the relatively shallow water of Santa Monica Bay in particular, by which a definite figure can be established.

Deeper Currents

The circulation in the deeper layers of the bay poses somewhat more of a problem. Current meter and drogue experiments seem to show that whenever an appreciable current is present the deeper water flows in the same general direction but with a substantially lower velocity. There is some indication from current meter data that deep currents may sometimes flow in a direction different than that of the surface layers, but this is by no means certain. When such differential flow was indicated the deeper currents usually were slow, less than 0.2 MPH, and so lay within the range where the current meters were inaccurate both with respect to direction and velocity. On purely argumentative and theoretical grounds, it is not impossible that currents near the bottom in the deeper parts of the bay may depart somewhat from the direction of flow at the surface, and it is not at all unlikely that they may do so in regions of complicated topography such as the heads of the submarine canyons off Redondo and Santa Monica. But over the bay as a whole there is no basis in fact for supposing that deeper currents may move out of the bay when the surface currents are directed toward shore.

The deeper circulation may be related to the divergence in surface current pattern which was found to exist in the central part of the bay. Whenever such a divergence exists, subsurface water must be brought to the surface. This might be reflected in lower surface temperatures or higher salinities in the region of divergence, but apparently the rate of upwelling in this area was so slow that in view of the relative uniformity of temperature and salinity conditions normally found in the inshore area, and of the shallowness of the water, the presence of such deeper water was completely disguised. It was often true that whenever a thermocline existed offshore, a similar marked temperature gradient was absent inshore, but because of the probable intensification of vertical mixing as one approaches the beach and the shoaling of the water, it cannot be concluded that the loss of a thermocline necessarily was due to the divergence and its accompanying upwelling. In short, there is no reason to assume that herein lies a mechanism of sufficient velocity by which material from the bottom in the offshore areas, particularly those adjacent to the sludge outfall, could by brought to the surface and inshore.

SUMMARY

Santa Monica Bay, a large crescent-shaped indenture of the coast, is in open communication with the ocean over the continental borderland of southern California,and the characteristics of the water in the bay are mainly controlled by the conditions farther from shore. Protected as they are by the offshore channel islands and the mountains to the north, the

waters in the bay are generally calm with only light to moderate afternoon seas, and low short swells to disturb the surface. Rarely, winds of Force 5 or greater blow from the northwest causing rough water in the southern and central part of the bay, but leaving the protected northern portion still in a state of near-calm. A swell with a period longer than 10 seconds is rare. Destructive waves are, therefore, nearly unknown in the bay except in the vicinity of Redondo where the bottom topography causes extreme modifications of the wave trains in the surf zone.

Current action in the waters is likewise gentle. It is established primarily by winds, and since they are usually of low velocity, the resulting wind drift and density currents are also slow. In the shallow nearshore area there is an oscillating motion due to the tides. Such tidal motion is normally parallel to the coast, but is frequently modified by density currents which also move in a north or south direction parallel to the eastern shores of the bay.

Because the water moves slowly in and out of the bay and because the net motion is determined by the interaction of several different forces, complicated patterns of water structure result. The Shelf Water Mass, which exhibits characteristics of deeper water from over the continental borderland, is almost always capped nearshore by a warm low-salinity water unit originating from the Hyperion outfall, Ballona Creek, and the Edison Company power plant. At times, this unit may become so dominant that it establishes density slopes and subsequent water motion over and above that normal

to the shelf water. Under such conditions a rather strong flow to the north along the coast is apparent. Other water units with colder or warmer temperatures, but with normal salinities occur at intervals in various parts of the bay and are related to minor complex patterns of currents. Some of these patterns recur with a frequency that can be correlated with weather conditions on a seasonal or non-seasonal basis. Others represent single isolated instances of unusual reactions by the water to weather and tidal conditions that happened to occur concurrently. Because the patterns of water units are complex, as are the resultant currents, prediction of water motion under a given set of conditions is still somewhat hazardous with the data at hand. However, the currents are by no means erratic and the net motion over a period of several days can be forecast with a reasonable degree of accuracy.

Water Temperature

Thermoclines and substantial temperature differences between the surface and bottom water were best developed during the summer. These temperature conditions are most favorable for the suppression of the effluent below the surface, although even then the rising sewage may reach the surface.

Inversions were characteristically present in the boil area, indicating the turbulent nature of the rising effluent column. Inversions were also encountered in both the southern and northern reaches of the bay where upward displacement of

subsurface water commonly occurs. These latter inversions do not reflect any essential instability of the water column.

Water Masses and Units

The water in the bay has been classified according to temperature salinity relationships as follows:

- Shelf Water Mass - 48° to 73°F, 33.0 to 33.5 o/oo
  - Surface Water Unit - 48° to 73°F, 33.0 to 33.5 o/oo
    - Subunit 1 - 60° to 62°F, 33.5 o/oo
    - Subunit 2 - 64° to 66°F, 33.5 o/oo
    - Sewage Field Subunit - 75° to 58°F, 0 to 33.4 o/oo
    - Intermediate Subunit - 54° to 57°F, 0 to 33.5 o/oo
  - Subsurface Water Unit - 53°F, 33.5 o/oo
- Slope Water Mass - 46° to 50°F, 33.6 to 34.3 o/oo
- Basin Water Mass - 43°F, 34.3 o/oo

The seasonal distribution of the various water units shows a biannual variation. The nearshore waters are normally colder than offshore waters in the winter season, November through May, and warmer in the summer, June through October. More or less steady state conditions exist along the Malibu and Palos Verdes coasts. Here cool water is adjacent to shore throughout the year. The conspicuous area of cold water along the Malibu coast is due either to a vertical displacement of isotherms following a period in which warm surface water is removed from the coast by westerly winds, or to active upwelling. The cold area to the south is due either to an upward displacement of cool water near the coast associated with the presence of a southerly current in that area, or to

the intrusion of cold water from deeper levels caused by the passage of tidal currents over a shallow bottom of complicated submarine topography.

The sewage field determined from temperature distribution is embodied in a large unit of slightly diluted sea water varying in thickness from 5 to 20 feet and covering an area of from 10 to 20 square miles. However, it should be remarked that the field thus determined by refined methods is considerably larger than that detectable by visual observation or by other qualitative standards.

Temperature and the Rising Effluent

The effective heat contributed to the bay from man-made sources is now 3.9% of the total amount in summer and 10.7% in winter. These figures will rise to 10.7% and 18.7%, respectively, when installations that are now being planned are placed in operation.

Most of the sea water for initial mixing with effluent from the existing outfall is derived from layers at or near the bottom. Thus, considering the annual range of bottom temperatures and the spread between the bottom and the surface waters, both sludge and effluent will rise to the surface as visible boils when normal winter temperature conditions exist. In summer, due to the greater temperature differential between bottom and surface, they may sometimes be at least partly suppressed.

Water Temperature and Related Motion

On the assumption that density currents can exist in shallow water as well as in the open ocean, an attempt is made to develop a qualitative method by which at least the general patterns of flow can be derived from horizontal temperature distributions in Santa Monica Bay. A general correspendence existed between the drift of drogues and the current directions deduced from the slopes of isothermal surfaces. In general, the flow from thermal slopes was toward the south during the winter period, and to the north during the summer. This is correlated with the annual cycle of wind conditions.

Water Salinity and Nutrients

The salinity of the water is essentially uniform (33.5 o/oo) from a depth of 40 feet down to the approximate break in slope (300 feet) at the outer edge of the shelf. In the surface layer, above 40 feet, salinities almost never rise above 33.7 o/oo, and usually lie between 33.55 o/oo and 33.60 o/oo. Salinities lower than 33.50 o/oo are found in the region of the Hyperion outfall, Ballona Creek, and the mouths of small canyons leading from the Santa Monica Mountains. There is no significant seasonal variation in salinity.

Average dilutions of effluent from the surface boil at Orange County and Hyperion range from 15 to 30 parts of sea water to one part effluent. At Whites Point the average dilution is 1:50. In the summer months, the limits of the

sewage field dilutions of 1:300 are more easily determined from salinity data than from temperature because the temperature of the effluent is nearly that of the surface layers in the bay. The nutrient salts, in concentrations much greater than that normally found in shelf water, were confined to an area within a few thousand feet of the Hyperion outfall. The small pockets of high concentration were distributed erratically throughout the effluent field. Variations in nutrient concentrations between the Orange County, Whites Point, and Hyperion outfalls are believed to result from differences in the character of the effluent discharged. Oxygen concentrations in the vicinity of the outfall indicate no serious areas of oxygen depletion during the time of the survey.

Transparency

The transparency of the water in Santa Monica Bay is controlled partly by plankton, but primarily by the amount of detrital debris contributed from the mountains, hills, and low coastal plains bordering the bay. Rocks in the mountains and hills are mainly fine-grained loosely consolidated shales and sandstones so that material eroded from them and carried to the bay during infrequent rains is usually in the clay to fine sand particle range. The resultant turbidity in the waters within a mile of shore is normally high and the transparency subsequently is lower than desirable from an aesthetic point of view. During the summer and fall a relatively high turbidity is maintained by wave action. The

depth to which a Secchi disc can be read in these waters is usually less than 15 feet. With increasing distance from shore the amount and size of detrital fragments in the water naturally decreases. A consequent increase in transparency occurs until at a distance of 10 to 12 miles from shore an average transparency of 30 to 40 feet exists.

As the sewage boil over the outlet of the Hyperion outfall is approached, a continuous decrease in transparency occurs until in the boil itself, a Secchi disc can often be seen no deeper than one foot. For a distance of about two miles around the outfall, the transparency is normally less than 10 feet. Such a condition would, of course, be relieved if the outfall were removed, but the increase in transparency would be no more than 5 feet except under the most unusual conditions, due to the natural turbidity of the inshore water.

Circulation of Santa Monica Bay

The currents in Santa Monica Bay were measured by current meters, drogues, and drift cards. Current velocities were generally low. With current meters, the maximum velocity measured was 0.45 MPH, but most were less than 0.25 MPH.

Drogues were used to measure subsurface currents at depths of from 15 to 90 feet. Velocities were somewhat greater than those observed with current meters or drift cards, at 15 feet varying between 0.17 and 1.07 MPH. At greater depths velocities were lower than near the surface; between 0.17 and 0.46 MPH at depths of 75 to 90 feet. There was no significant difference in direction of flow between 15 feet and deeper level.

On fourteen cruises in the bay, between September 9, 1955 and August 21, 1956, 5,326 drift cards were released, of which 34% were recovered. Included in the patterns were stations near the terminals of the proposed sludge and effluent outfalls.

During the period of September 8, 1955 through February 16, 1956, the pattern of surface flow was variable, but the bay appeared to be well flushed, at least intermittently, by relatively strong currents directed either to the north or to the south. Of the five cruises during this interval, on only one (September 29, 1955) was there a general drift to the east and inshore from part of the area. On one (September 8, 1955) the initial drift was to the north and outside the bay, and on the other three the surface waters appeared to have been removed almost completely from the bay (December 29, January 18, and February 16).

Beginning on February 22, and extending through the cruise of August 9-10, 1956, the predominant drift was toward the shores of the bay, but frequently superimposed upon this was a moderate southerly or northerly component. Many of these later cruises, as well as the earlier one of September 29, 1955, showed signs of a divergence in the current as the water approached the shore. It is most clearly marked on the charts showing drift card returns of September 29, Area III and of August 9-10, where returns from stations north of a particular line were separated by an evident gap from those below the line. The cruise of August 19-20, 1955, with its strong northward component and low velocities suggests a return to conditions noted in the fall of 1955.

From all sources of information on surface currents, it can be stated that outside the littoral zone velocities of greater than 0.6 MPH are rare, those of the order of 0.4 MPH are infrequent, and usual velocities are 0.3 MPH or less. Maximum velocities are usually found in the southern inshore portion of the bay.

More important than the maximum velocities for special regions such as the southern end of the bay, are the data obtained from the stations located at the approximate sites of the proposed sludge and effluent outfalls. In no case was a velocity greater than 0.58 MPH recorded from a sludge or effluent outfall station. The single case of a maximum velocity greater than 0.31 MPH was recorded from the effluent station on June 19, 1956. These figures are significant because the velocities represent the limits within which coliform organisms from primary effluent of the type found at Hyperion will be reduced to legal specifications at the beach. This matter is discussed in detail in the section of the report of the University of Southern California which deals with the bacteria, but the general conclusion is that under the conditions specified, the coliform standards as now established by the State Water Pollution Board probably will be met.

Velocities in excess of those values will occur in the central part of the bay, but it is believed that the frequency of such rapid flow will certainly be less than 20%.

Deeper currents in the bay flow generally in the same direction as the surface currents, but at a lower velocity. This conclusion may not hold in special regions of complicated bottom topography, but it will apply to the waters over most of the shelf. There appears to be no mechanism by which deep water can be continuously brought to the surface with any appreciable speed.

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